Robots at the Threshold: Outdoor Work in a Radioactive World

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This paper specifies a full division of labor for a radioactive world in which people remain indoors while robots perform *work* outdoors—not just mapping and logging. We define how aerial, ground, and fixed manipulators plow fields, harvest crops, sweep streets, repair power and water lines, install shielding, fight fires, haul waste, service vehicles, and build new infrastructure—end-to-end, from task planning to decontamination. The city is partitioned into H-zones (human habitats), A-zones (airlocks/decon gates), and R-zones (everything outside). Within R-zones, we enumerate robotic jobs, required tools (grippers, shears, cutters, HEPA vac heads, seeders, sprayers), autonomy levels, teleoperation triggers, and cycle times. We also detail support systems: garages, wash bays, filter handling, battery/fuel logistics, spare parts, and shift scheduling. Each job flow ends at an A-zone with dose gating and chain-of-custody so goods and services cross the threshold cleanly. Finally, we address governance and equity so the safest services—clean streets, reliable utilities, fresh food—reach all neighborhoods first. The goal is operational clarity: what robots do, with what tools, in what order, under what standards, and how households and municipal ops monitor performance without stepping outside.

Keywords: radioactive world, outdoor robotics work, UAV, UGV, telemanipulation, agriculture robots, street HEPA sweepers, utility repair robots, firefighting drones, shielding deployment, hot-cell maintenance, waste handling, decontamination airlocks, RO/IX support, fleet management, work instructions, ALARA, equity of service.

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1) Problem & Operating Model

1.1 Why all outdoor work is robotic in a radioactive world

First principles (ALARA → ALARR): In chronic contamination, the ethical and economic optimum is not "as low as reasonably achievable" for *people*—it is **as low as reasonably required** (**ALARR**) because robots can accept exposure within engineered limits. Shifting outdoor work from humans to machines eliminates the highest-variance exposure pathways: **resuspended dust, hot spots, bone-seeking nuclides via hand-to-mouth, and accident-driven dwell time**.

What makes outdoor human labor indefensible (operationally):

- **Dose volatility:** Wind, traffic, and surface abrasion push particulate levels from safe to unsafe in minutes; robots can pause or reroute automatically.
- **Task coupling:** Real work is *not* a quick meter reading; it's hours of sweeping, cutting, digging, hauling—exactly the durations where internal dose accumulates.
- **Error amplification:** A torn glove, a forgotten mask fit-check, or an unlogged hotspot can multiply dose; robots enforce **software guardrails**.
- **Logistics scale:** Cities require continuous **street hygiene**, **utility repair**, **ag harvesting**, **storm response**. A human workforce would consume PPE and testing capacity at unsustainable rates.
- **Equity & trust:** If some neighborhoods still rely on outdoor human labor, they bear higher risk. Robotic work **standardizes safety** across zip codes.

Business case in one line: Robots convert **hazard time** to **data time** and **machine wear**, which are predictable, schedulable, and insurable.

1.2 Three-zone city (H/A/R) and service-level objectives (SLOs)

City partitioning

- **H-Zones (Human habitats):** Positive-pressure interiors (HEPA/H14), RO/IX tap water, covered prep surfaces, and sealed delivery lockers. People live, learn, cook, worship, and work **without routine respirable or ingestion pathways**.
- **A-Zones (Airlocks & docks):** Physical choke points where *everything* crossing the threshold is **decontaminated, inspected, and dose-gated**. Includes goods locks, waste locks, and tool/service locks.

- **R-Zones (Robot world):** All exterior spaces—streets, fields, roofs, rights-of-way, utility corridors—operated exclusively by **UAVs, UGVs, and fixed/telemanipulated systems**.

Interfaces that make the model safe:

- **Chain of custody:** Each tote/parcel carries a **digital passport** (origin → decon steps → gate reading → release decision).
- **Monodirectional hygiene:** Dirty→clean flow is physically enforced (interlocks, check valves, purge cycles).
- **Data symmetry:** Raw spectra, air counts, and route logs are **exportable**, not summarized into opaque "scores".

Citywide SLOs (service-level objectives)

SLOs define *how well* robots must perform so humans never need to go outside for routine reasons. Targets are set so that misses trigger **automatic mitigations** (e.g., indoor HEPA cadence bumps) and **escalations** (e.g., extra sweeper loops).

Domain	SLO (target)	Why it matters	Auto-mitigation on miss
Dose map refresh	≥ **95%** of public right-of-way re-mapped every **24 h** with cell-level confidence ≥ 90%	Keeps hotspot intel current for routing and shields	Route "avoid" flags + redeploy survey UAVs; slow noncritical outdoor tasks
Street dust load	Curb-to-catch-basin PM reduction **≥ 40%** vs baseline; every block swept **daily**	Cuts resuspension (inhalation + food surface dust)	Add sweeper loop; raise indoor HEPA runtime in affected H-zones
Food tote gate pass rate	**≥ 99.5%** pass on first decon + gamma gate	Prevents contaminated goods from entering H-zones	Quarantine lot; reroute clean reserve; notify co-op lab
Utility fault response	First robot on-site in **≤ 15 min**; isolation/temporary service in **≤ 60 min**	Avoids human field crews; stabilizes water/power	Dispatch backup crawler; pre-staged portable shields

Domain	SLO (target)	Why it matters	Auto-mitigation on miss
Delivery latency (equity)	90th percentile **≤ 2×** median across zip codes	Equal service = equal protection	Priority routing to lagging zip codes next cycle
Waste pickup	**100%** of tagged bins collected **≤ 24 h**	Avoids informal handling/disposal	Dispatch surge mule; open overflow lockers
Airlock throughput	Goods lock cycle **≤ 6 min** (P95)	Prevents human "workarounds"	Spin up parallel lock; defer noncritical inbound

Key performance indicators behind the SLOs

- **Dose avoided (human):** Σ human outdoor hours = **0** routine; cumulative public worker dose trends **flat**.
- **Robot health:** Mean time between decon failures; filter ΔP trends; battery SOC margin at docking.
- **Data quality:** % missions with uploaded raw spectra; % cells with MDA below threshold; calibration drift alarms/week.
- **Compliance:** % parcels with complete passports; % airlocks with up-to-date sanitizer and filter cassettes.

Governance triggers (what happens when SLOs slip)

1. **Automated controls:** Increase indoor HEPA runtimes, postpone nonessential outdoor tasks, raise sweeper cadence, widen geofences around hot cells.
2. **Operational surge:** Spin up reserve fleet; extend robot shifts; open mutual-aid links with neighboring depots.
3. **Public notice:** Post dashboard tiles (what slipped, where, how mitigated, when back to green).
4. **Root-cause review:** Within 72 h—sensor drift, weather anomaly, fleet shortage, or process breach—and a published fix.

Design guardrails

- **No human override to "just step out."** If a job can only be done by a person, the job is **redesigned** (tooling, shielding, or telemanipulation).
- **Outdoor cameras respect privacy by default** (window/face blurring; indoor boundaries).
- **Open standards** for passports, spectra, and route logs so multiple vendors can coexist and communities can audit.

Bottom line: The H/A/R city is a *system contract*: humans promise to stay indoors for routine life; robots promise to keep the outdoors livable—clean streets, stable utilities, safe food pathways—**at measurable, enforceable levels of service**.

2) Fleet & Facilities

2.1 Robot types (UAV, quadruped, tracked, wheeled, boom/manipulator, hot-cell)

Aerial—UAV (multirotor / VTOL)

- **Roles:** plume/dose mapping, roof inspection, gutter purge, package relay, thermal search, foam/water spot drops.
- **Spec bands:** 2–6 kg payload; 30–40 min endurance; IP54+; RTK GNSS; LiDAR or stereo; NaI/$LaBr_3$ pod option; quick-swap battery.
- **End-effectors:** gimbal sprayer, micro winch, grabber hook, perching foot.
- **Teleop triggers:** high winds, close-in manipulations, unknown obstacles.

Quadrupeds

- **Roles:** stairs/rough terrain, interior plant patrol, valve reads/turns, tote nudge, door handle pulls.
- **Spec bands:** 10–14 kg payload; 90–120 min; IP54; pan-tilt cam; small manipulator (5–10 N·m).
- **End-effectors:** parallel gripper, smear pad, nut-runner, vacuum wand.
- **Teleop triggers:** tight valves, brittle debris, casualty drag.

Tracked UGV (compact)

- **Roles:** pipe galleries, culverts, rubble; towing sleds; push brooms; shield tile placement.

- **Spec bands:** 20–60 kg payload; 2–4 h endurance; low CG; front dozer blade.
- **End-effectors:** squeegee skid, HEPA head, magnetic sweeper, shear.
- **Teleop triggers:** cutting/bagging operations, near-hotspot work.

Wheeled UGV (mule / sweeper)

- **Roles:** tote logistics, curb-to-catch-basin HEPA sweeping, brine/spray, snow blade.
- **Spec bands:** 100–300 kg payload; 6–10 h; hot-swap packs; Class-1 e-brake; ISO 3691-4 safety.
- **End-effectors:** roll-off tote deck, lift-gate, sticky-roller cassette, blower/air-knife.
- **Teleop triggers:** crowded alleys, blocked curbs, unusual pedestrians/animals.

Boom/manipulator bases (mobile)

- **Roles:** saw/cut/bolt, clamp leaks, set shields, place sandbags, remove panels.
- **Spec bands:** 6–DOF arm, 20–40 kg lift @ 1 m; force/torque sensing; tool-changer; 360° cameras.
- **Tools:** nut-runner, grinder, reciprocating saw, hole saw, core sampler, vacuum nailer, sealant gun.

Hot-cell manipulators (fixed / through-wall)

- **Roles:** cut, bag, segregate, and repackage “yellow-tag” items; filter cassette swaps; decon of tools.
- **Spec bands:** master-slave or teleop arms with shield window; negative-pressure cell; floor drain to sludge drum.
- **Tools:** shear, gripper, bagging rings, tie-off tool, drum crimper, wipe sampler.

2.2 Garages: charging/fueling, spares, wash/decon lines, filter press, sludge handling

Layout (dirty→clean flow)

1. **Inbound lane (dirty):** drop shields/cassettes → **pre-knockdown** (air knives + HEPA capture).
2. **Wash line:** low-splash mist, squeegee rollers, rotary brush for tracks; conductivity-controlled rinse.

3. **Verification gate:** gamma portal + vision for residue; fail → recirculate.
4. **Maintenance bays (clean):** battery/fuel swap, sensor cal, tire/track service.
5. **Spares room:** labeled kits (belts, blades, seals, nozzles), serialized batteries, sacrificial skins.
6. **Charge/fuel farm:** vented battery racks (BMS monitored), hydrogen/propane cages if used; spill berms.
7. **Control room:** dispatch, telemetry wall, spectra ingest, incident desk.

Utilities & waste

- **Water loops:** two circuits—wash (recirc through bag filter + ion-exchange) and final rinse (RO/IX fresh).
- **Filters:** inline bag filters (5→1 µm) before IX; ΔP sensors; **filter press** for fines → cake → **yellow drums**.
- **Sludge handling:** closed sump → polymer dosing → press → drum; barcode drums; weigh, store in shielded pallet rack.
- **Air:** local capture hoods, MERV-13 prefilters → H14 HEPA; negative pressure in wash zone relative to maintenance bay.

SOP highlights

- **Arrival:** scan robot ID → auto-import route/dose logs → decide wash recipe (standard/deep).
- **Decon recipe:** air-knife 60 s → mist 120 s → squeegee 2 passes → final RO rinse 30 s → 90 s drip → portal verify.
- **PM cadence:** every **25 h** run time (light), **100 h** (full); calibration check weekly; firmware on off-shift.
- **Tool chain-of-custody:** tool-changer logs which tool touched which job; tools that left the garage must reenter via wash line.

Safety

- Color-coded zones; interlocks between dirty/clean doors; eyewash/shower; battery fire blankets; spill kits.
- **Alarms:** IX breakthrough (conductivity ↑), HEPA ΔP high, portal gamma excursion, sump level, hydrogen detection.

Staffing (inside only)

- **Planner/dispatcher**, **wash tech**, **MRO mechanic**, **filter/sludge tech**, **data QA**. No one crosses into R-zone.

2.3 Airlocks: goods, tools, waste; gamma gates; chain-of-custody

Airlock types & geometry

Lock	Purpose	Size (internal)	Key features
Goods lock	Food, parcels, meds inbound	1.2×1.2×2.2 m (single tote) or 2.4×2.4×2.4 m (pallet)	Dual interlocked doors; mist/dry decon; **gamma gate**; belt scale; barcode/QR scanner; UV-C option
Tool/service lock	Tools/parts outbound & return	1.5×1.5×2.2 m	Tool tag reader; torque/inspection bench; vision check for residue
Waste lock	Bins outbound	2.0×2.0×2.2 m	Compactor; liner sealer; weight + photo log; negative pressure to corridor

Common stack

- **Airflow:** dirty side negative vs corridor; **HEPA scrub** exhaust; make-up air through MERV-13 + HEPA.
- **Decon:** selectable cycles—air-knife only / mist (RO + chelator) / dry wipe by telemanip gloves.
- **Sensing:** γ portal (NaI/CZT) with auto background; particle counter; cameras; load cells.
- **Controls:** PLC with door interlocks; cycle recipes; audit log; emergency stop that seals both sides.

Goods lock cycle (example, P95 ≤ 6 min)

1. **Load:** robot places sealed tote; outer door closes; **photo + weight + QR** captured.
2. **Air-knife:** 45–60 s; dust captured to HEPA cartridges.
3. **Mist + squeegee:** 60–90 s; low-splash; drains to sump.
4. **Gamma gate:** 60–120 s count; compare to **release criteria** (geometry, MDA posted).

5. **Decision:**
    - **Release:** inner door unlocks; tote rolls into H-zone vestibule.
    - **Hold:** tote to quarantine cubby; alert lab for longer count.
    - **Reject:** return to robot; tag lot "yellow."

Tool lock cycle

- Outbound tools: pack + tag → lock prints **tool passport** (ID, last wash, calibration).
- Return tools: same as goods but recipe emphasizes crevice rinse and vision inspection; if fail twice → hot-cell.

Waste lock cycle

- Bin sealed & tagged inside H-zone → lock verifies seal → negative-pressure equalization → outer door releases to robot pick. Photos + weight uploaded to route.

Chain-of-custody data (all locks)

timestamp, lock_id, cycle_id, operator_id(optional),

direction(in/out), item_type(tote/tool/bin), item_id, lot_id,

photo_url, weight_kg, decon_recipe, gamma_count_sec, mda_cs137_bqkg,

decision(release/hold/reject), exception_notes, qr_for_passport

Failure modes & mitigations

- **Gamma false positive (K-rich food):** spectral check (1460 keV K-40) → allow release with note.
- **Stuck door:** both sides hard-seal; notify maintenance; reroute deliveries to adjacent lock.
- **HEPA ΔP high:** auto-throttle cycle rate; page filter tech; display ETA to users.
- **Power dip:** UPS holds controls; doors fail-safe closed; resume cycle when stable.

Human interface (inside)

- **One-touch presets:** "Food tote," "Meds," "Tools," "Waste."
- **Status lights:** Red (cycling), Yellow (hold), Green (release ready).
- **Accessibility:** quiet pumps, low thresholds, tray height ≤ 1.0 m, large fonts on passports.

Design principles

- **Monodirectional hygiene** (dirty→clean).
- **Measured release** (raw spectra, MDA, photos).
- **No exceptions by convenience.** If it can't pass, it doesn't cross.

3) Agriculture & Green Assets

3.1 Field prep: cover installation, drip lines, tunnel films

(end-effectors: stake driver, film roller)

Objectives: Break soil–plant–dust pathways, standardize irrigation, and create low-deposition canopies robots can service without exposing humans.

Workflow (robot crew of 2–3 UGVs + 1 UAV scout)

1. **Survey & stake grid (Day 0)**
    - UAV generates centimeter mesh; UGV places corner flags; geofence pushed to fleet.
    - **End-effectors:** vibro **stake driver**, laser line projector.
    - **QC:** stake spacing ±2 cm; tension anchors logged.
2. **Bed forming & drip lay (Day 1)**
    - Tracked UGV with **bed shaper** raises 10–15 cm berm; second UGV lays **dual drip lines** (flush ports every 25 m).
    - **QC:** flow test each zone (target 1–2 L/h/emitter); GPS-stamped pressure readings.
3. **Mulch & tunnel film (Day 1–2)**
    - **Film roller** UGV applies black mulch; **hoop placer** sets ribs at 1.2–1.6 m spacing; **film puller** stretches/locks low-tunnel plastic; edge trench & backfill.
    - **QC:** camera checks for wrinkles/tears; tension force sensor ≥ spec; seams heat-seamed at overlaps.

4. **Access doors & ports (Day 2)**
    - Robots cut zip-door apertures every 20–30 m; install magnetic flaps and **service sleeves** for sprayer/feeder wands.
    - **QC:** door seal leak rate ≤ X L/min (fan test); sleeves tagged in map.

KPIs: hectares prepped/day; drip zone pass rate; film integrity (% seams passing); wind uplift incidents (target 0).
Teleop triggers: rocky ground (stake refusal); unexpected debris; film tear >15 cm (switch to patch routine).

3.2 Planting & care: seeders, nutrient injection, covered spraying; weed & pest control under covers

A) Planting

- **Direct seeders (UGV):** vacuum singulation wheels calibrated per seed size; **brush bar** to close slit; onboard seed scale for drift detection.
- **Transplant robots:** arm with soft **vacuum cups** and depth shoe; tray handling from pallet.
- **QC:** emergence cameras 3–7 days later; re-seed algorithm for missed spots.

B) Irrigation & fertigation (nutrient injection)

- **Inline venturi injectors** driven by UGV pump skid; EC/pH probes in loop; PID to recipe.
- **Recipes:** RO make-up + certified salts (lot-logged); leach every N cycles to prevent salt creep.
- **QC:** EC within ±0.1 mS/cm; pH ±0.1; flush log recorded.

C) Covered spraying (inside tunnels/low tunnels)

- **Sprayer wand UGV:** telescoping boom that enters via **service sleeve**; electrostatic nozzles minimize volume; camera verifies coverage.
- **Allowed agents:** food-safe acids/soaps/biocontrols from **sealed lots**; no dust-creating powders.
- **QC:** droplet deposition cards read by vision; overspray alarms at door seams.

D) Weed & pest control (non-fumigant)

- **Thermal weeder sled** (propane/electric) at 300–400 °C pass for pre-emerge; **steam lance** around stems.
- **Mechanical micro-hoe** for intra-row; **suction bug head** (low-damage vacuum) for pests; **pheromone trap placement** via arm.
- **Vision:** pest hotspot classifier (on-bike model) dispatches targeted passes; recheck next cycle.

E) Environmental control

- **Vent bots** crack/close end flaps by forecast; humidity purge with inline HEPA blowers if condensation observed (to prevent drip-borne dust).
- **QC:** leaf wetness sensors; canopy ΔT limits.

KPIs: emergence rate; EC/pH adherence; pest counts per trap; spray rework rate; water use per kg yield.
Teleop triggers: disease outbreak beyond threshold; torn film; clogged emitters beyond auto-flush recovery.

3.3 Harvest: cut, sort, tote loading; robot wash → food-grade totes → A-zone workflow

A) Harvest operations

- **Cut/pick:**
    - **Leaf/fruit crops:** twin **scissor grippers** with force control; inline weight cell per pick.
    - **Root crops: lift & shake** fork; peelable roots routed to wash line; soil retained outside.
- **Sort & grade:** RGB+NIR camera box; reject tray for defects; grade A/B lanes.

B) Tote & traceability

- **Food-grade totes** (vented bases, smooth interiors) pre-washed by robots; **liner bags** from sealed rolls.
- Every tote receives a **QR passport**: bed ID, robot ID, time, weight, pre-wash pass, target customer/batch.

C) Robot wash and pre-gate hygiene

- **Robot wash** (outside field edge): air-knife → low-splash RO mist → squeegee → portal check.
- **Product pre-rinse** (if dusty crop): RO spray tunnel; **never** reuse rinse liquor.
- **Seal:** liner heat-seal or tamper tag; lid on.

D) Transfer & A-zone workflow

1. Logistic UGV hauls sealed totes to **Goods Airlock**.
2. **Airlock cycle:** air-knife → mist → **gamma gate (60–120 s)** → decision.
3. **If hold:** tote to quarantine rack; co-op NaI spectrometer 60–240 min; release on pass or return to outdoor cold room.

E) Worker-inside roles

- Tablet review of **lot passports**; pick tickets; kitchen staging. No outdoor contact.

KPIs: kg/hour picked; tote first-pass release ≥99.5%; gamma "hold" rate; damage <2%; time field→table.
Teleop triggers: jammed cut head; product lodging; unexpected portal reading (route to hold & re-image).

3.4 Orchard / roof gardens: pruning, fruit pickers, lift drones, gutter-clean bots

Orchards

- **Pruning UGV:** 6-DOF arm with **powered loppers**; LiDAR skeletonizes canopy; cut library (spur/heading cuts by species).
- **Thinning & picking:** soft **vacuum pickers** with bruise sensors; adjustable suction; **conveyor to tote**.
- **Mowing/understory:** low deck with **mulch skirt**; dust-minimizing speed; edge brushes push debris inward for capture.
- **Spray under covers:** tunnel rows with retractable film or netting; sprayer enters via end flap; drift sensors.

Roof gardens & green roofs

- **Lift drones** (winch, 5–15 kg) shuttle crates; **roof mules** carry loads to lockers.
- **Gutter-clean bots:** tracked crawlers with **HEPA vac head** + squeegee; debris bagged and tagged; portals at roof access.
- **PV wash/inspect:** boom robot with squeegee bar; RO water only; inline conductivity alarm; panel thermal scan.

Tree & structure safety

- **Tarp deployers** for dust events; ballast bags placed at corners; UAV inspects seam lift.
- **Anchor checks** logged quarterly; force/tension sensors flag loosening.

Data & passports

- Fruit lots: **block–row–tree** in QR; spray history, pick date, tote ID.
- Roof harvests: building ID, deck, bed, gutter status photo pre/post.

KPIs: picks/hour per robot; bruise rate; gutter flow restored (%); PV wash cycles per month; roof tote release rate.
Teleop triggers: high wind (auto roost); branch under tension; loose parapet cap; slippery roof alarms.

Standard safety & hygiene threads across §3

- **Monodirectional hygiene:** soil stays outside: no raw-soil contact with totes or robot wash pads.
- **Water discipline:** RO/IX for any food contact; non-potable loops never cross.
- **Lot integrity:** everything grown/handled gets a **passport** that survives all steps; photos at each handoff.
- **No human fieldwork:** if a task still “needs hands,” redesign with a tool, shield, or telemanip cell.

4) Street & Public Space Hygiene

4.1 HEPA sweepers and sticky-roller UGVs: curb-to-catch-basin routes, dust KPIs

Mission: Reduce re-suspended dust (chief ingestion/inhalation vector) by removing fines from the *curb channel → inlet grate → catch-basin* path, every block, every day.

Platforms

- **HEPA Sweeper UGV (wheeled, 100–300 kg payload):** twin side brooms → center vacuum head (H14 HEPA with ΔP sensors), curb-follow LiDAR, gutter nozzle.
- **Sticky-roller UGV (compact tracked):** replaceable adhesive cassettes for sidewalks, medians, station platforms, stair treads.

Route design (autonomy-first)

- **Primary loop:** right-hand curb, 0.25–0.35 m gap, 6–8 km/h; **dwell** 8–12 s per grate.
- **Secondary loop:** sidewalks/medians nightly (roller bot), 3–4 km/h.
- **Edge cases:** bus stops, bike corrals, construction cones → geofenced slow zones (≤3 km/h) with teleop takeover on prompt.

SOP (per block)

1. Side brooms lift curb debris to vacuum path; head pressure auto-sets via ΔP.
2. At grates: pause, **vac wand** dip 0.3 m into throat; snapshot photo.
3. Log **bag ΔP**, **mass collected**, **GPS cell ID**; if ΔP ≥ threshold → route to garage filter swap.
4. Daily **catch-basin count** (seen/serviced) reconciled against GIS.

Decon on return

- Air-knife → low-splash mist → squeegee → portal gamma; bag filter to **filter press**; cake to "yellow" drum.

KPIs

- **Coverage:** ≥ 98% of curb meters/day.
- **PM reduction:** curb strip $PM_{2.5}$ **≥ 40%** vs baseline sensors.
- **Grate service:** ≥ 95% of mapped grates touched daily; photo evidence.
- **Filter health:** HEPA ΔP "yellow" < 5% of hours; "red" = 0 route minutes.

- **Equity:** 90th-percentile time-to-service ≤ 2× median across zip codes.

Teleop triggers

- Pedestrian crowding; construction obstructions; ΔP spike (possible clog); portal “fail” on prior mission; animal entanglement.

4.2 Spot cleanup: vacuum wands, squeegee skids, absorbent deployers for wet hotspots

Use cases: Dumped soil, burst trash bags, fine-powder spills, oily patches, puddles with visible sheen, alley dumps under eaves.

Tooling (modular to UGV base)

- **High-lift vacuum wand** (HEPA back-end; clear barrel for visual).
- **Squeegee skid** with adjustable downforce and perimeter lip to corral slurry.
- **Absorbent puck deployer:** drop-place cellulose/diatomaceous pads; timed pickup after dwell.
- **Micro-spray bar** (RO water + surfactant/chelating agent) for low-splash dampening.

Playbook (dispatch ticket → close)

1. **Classify** (vision model + operator confirm): dry fines / wet oily / mixed / unknown.
2. **Isolate:** place beacon cones (robot-deploy), set temporary **no-go geofence** for other robots.
3. **Dry fines:** mist-dampen → vacuum wand passes → sticky-roller follow-through.
4. **Wet/oily:** deploy absorbent pucks (grid), dwell 3–5 min → squeegee into pan → vacuum → secondary pass with fresh pucks if sheen remains.
5. **Mixed/unknown:** dampen perimeter to prevent lofting; escalate to **tool lock** sample for lab if color/odor anomaly.
6. **Verify:** after-photo + on-board PM reading; unlock geofence.
7. **Waste path:** sealed pan → goods/waste lock → compactor classification; absorbent tagged to drum.

KPIs

- **Response time:** P90 **≤ 30 min** from ticket to first pass.

- **Clearance: ≤ 2 passes** to below visual/PM threshold.
- **Re-soiling rate: < 10%** tickets reopen in 24 h.
- **Waste accuracy:** ≥ 99% correct stream (general vs “yellow”).

Teleop triggers

- Sheen travel toward storm inlet; unknown powders; portal “hold” on absorbent pan; crowds.

Safety guards

- Zero dry-sweep ever; spray volume limits to prevent run-off; storm inlet **curb socks** auto-deployed for wet tasks.

4.3 Snow/sand/dust events: plows, brine sprayers, tarp deployers; storm playbooks

Threats: Seasonal snow/ice; wind-borne sand; dust storms that spike PM and redeposit contaminants.

Fleet tools

- **Plow blades** (poly edge), curb-aware.
- **Brine sprayers** (RO brine only; calibrated 90–120 L/km two-lane equivalent).
- **Grit spreaders** (washed, graded aggregate; sealed bins).
- **Tarp deployers** for stockpiles/soil exposures (sandbag placer).
- **UAV scouts** with anemometer/PM to steer cadence.

Playbooks

A) Snow/Ice (48-h window)

- **T-24 h (forecast):** Pre-brine priority corridors, bus routes, clinic approaches; verify drains clear.
- **T-0 to +12 h:** Plow 2–5 cm thresholds; **no windrows** blocking inlets; follow with brine spot.
- **T+12 to +48 h:** Curb-to-catch-basin cleanup; vacuum slush from inlets to prevent refreeze.
- **Waste:** slush to sump → press → drum if classified “yellow.”

KPIs: pass-able lanes ≤ 2 cm residual; clinic/airlock frontage cleared P90 ≤ 60 min; inlet re-freeze tickets < 5%.

B) Sand (post-storm drift)

- **Scout:** UAV dune map; priority on crosswalks/ramps.
- **Clear:** plow to windrows → HEPA vac head lifts fines; aggregate larger than 2 mm to clean stock if non-yellow.
- **Seal:** apply dust-binding micro-spray on exposed soil edges; deploy **tarp** on piles.

KPIs: ramps/crosswalks P90 ≤ 90 min; PM drop ≥ 40% within 2 h; zero uncovered stockpiles after 6 h.

C) Dust storm protocol

- **Pre-event:** close construction soils; tarp deployers to all exposed piles; street sweepers run **pre-wash** loops; notify H-zones to **increase indoor HEPA runtime**.
- **During:** UAV PM watch; sweepers **pause** if vis < 100 m (avoid lofting), switch to **curb socks** at inlets; only spot dampening allowed.
- **Post:** full curb-to-basin sweep **within 6 h**; targeted sticky-roller on stations/doors; public dashboard tile “Back to Green” when corridor PM ≤ target for 2 consecutive hours.

KPIs: corridor PM normalization ≤ 6 h; % exposed soils tarped ≥ 99%; H-zone HEPA cadence bump on-time ≥ 95%.

Shared data, decon, and governance threads

Data model (per street cell, 25×25 m)

timestamp, cell_id, route_id, robot_id, task_type(sweep/spot/snow/dust),

pm25_pre, pm25_post, grate_id_list, hepa_deltaP, mass_collected_kg,

photoset_url, anomalies(flag+note), operator_id(optional)

Decon & waste

- All sweep/spot gear returns via **wash line**; bag filters through **filter press**; cakes to labeled drums; chain-of-custody scanned.
- Adhesive cassettes sealed; sticky waste never compacted with general trash.

Governance & equity

- Public map shows **coverage, PM deltas, and response times by zip**.
- SLO breaches auto-trigger **additional sweeper loops** and **indoor HEPA cadence bumps** in affected blocks.
- Contract clauses: vendors must expose **raw logs & photos**, not just "cleanliness scores."

Bottom line: Daily curb-to-catch-basin hygiene, rapid spot response, and storm playbooks—executed by a purpose-built robot fleet—turn the biggest urban dose amplifier (resuspended dust) into a **managed, measured, and steadily shrinking risk**.

5) Power, Water, and Gas Utilities

5.1 Power: line inspection (UAV), insulator wash, switchgear manipulation, portable shield placement

Objectives: Keep electrons flowing without sending humans outdoors; reduce flashover/dust fouling; restore service after faults; perform hot work via distance and shielding.

A) Overhead line inspection (UAV)

- **Platform/payload:** RTK UAV, zoom RGB + thermal, corona cam (UV), micro–LiDAR alt hold. Optional NaI pod to flag contaminated corridors.
- **Flight plan:** pole-to-pole at 5–8 m offset; crossarms at 2 angles; substation perimeter orbits.
- **Findings & auto-tags:** chipped insulators, bird nests, conductor strand breaks, hot clamps, vegetation encroach.
- **Deliverables:** pole ID → photo set + thermal; defect severity; "work ticket" for ground bots.

B) Insulator wash (hot stick drone or boom UGV)

- **Water:** RO only; conductivity sensor interlock (< 20–30 µS/cm).
- **Method:** UAV mist cone or UGV telescoping lance; low-splash; collector pans under drip when practicable.
- **SOP:** de-energized preferred; if energized, maintain clearance table; wind < 6 m/s.

C) Switchgear & recloser manipulation (UGV/telemanip)

- **Tools:** insulated hook, torque head, handle adaptor set, panel key kit.
- **Sequence:** visual confirm → torque/position confirm → operate → post-op photo + current/voltage sensor check.

D) Portable shield placement (UGV/boom)

- **Shields:** modular steel/lead/water walls on dollies; sandbagger for temporary berms.
- **Use cases:** dosey substation corners, cut sites, roadside hotspots.
- **Placement SOP:** route plan → set cones/geofence → drop mats → position shields → verify with dose probe.

E) KPIs & triggers

- **KPIs:** patrol closure ≥ 95% daily; defect-to-ticket < 10 min; energized wash pass rate ≥ 99%; SAIDI/SAIFI targets met; shield deploy ≤ 45 min from call.
- **Teleop triggers:** wind gusts, arcing detected, clearance doubts, unexpected public presence.

F) Decon

- Drones/booms through wash line; nozzle/hoses flushed with RO; collected rinse to sump → press → drum.

5.2 Water: valve robots, hydrant service, leak detection, main repairs (saw, clamp, weld)

Objectives: Keep potable loops tight and flowing; fix breaks without outdoor crews; maintain fire flow via robot-serviced hydrants.

A) Valve operation (UGV)

- **Hardware:** torque head (adaptive), socket set, depth camera to find nut, torque/turn counters.
- **SOP:** locate box → vacuum fines → fit socket → test-turn ¼ → record torque curve while closing/opening per ticket.
- **QC:** end-state (open/closed) verified by pressure/flow telemetry.

B) Hydrant service

- **Tasks:** bonnet remove, lube stem, replace gaskets, flush, flow test; cap with tamper seal.
- **Tools:** hydrant wrench end-effector, gasket kit, RO flush hose, flow meter.
- **QC:** flow/pressure log; photo of seat condition.

C) Leak detection

- **Acoustic:** clamp-on mics at valves; correlation across nodes; prioritize noisy cells.
- **Thermal/visual:** UAV thermal during cool hours; street wetness classifier; chloride strips for treated-water confirmation.
- **Pinpoint:** ground mic + short test digs with vacuum wand if needed.

D) Main repair routines

- **Temporary clamp (live):** saw to expose, sand-bag perimeter, dewater with vacuum, wrap clamp, torque pattern, leak check.
- **Cut-out & couple:** shield deploy → pipe saw → bevel & clean → couplings installed → recharge slowly.
- **Weld segment:** mobile shield → weld head (MIG/TIG) on boom; fume captured; slow cool; NDT (ultrasonic) if required.

E) Disinfection & water quality

- **Disinfection:** pre/post flush with RO; dose log; residual checks; boil-advisories avoided by controlled zones.
- **Backflow protection:** check valves at every robot hose; color-coded lines (blue potable; purple non-potable).

F) KPIs & triggers

- **KPIs:** leak locate ≤ 4 h; clamp install ≤ 2 h from pinpoint; water loss ↓ ≥ 25% YoY in pilot zones; hydrant PM completion ≥ 98%/yr.
- **Teleop triggers:** cross-utility strikes, sinkholes, public crowding, poor visibility.

G) Decon & waste

- Tools through wash line; spoil/dregs to sealed pans; chlorinated flush captured to sump treatment; swabs logged.

5.3 Wastewater/storm: grate clearing, CCTV crawlers, root-cutters, vacuum extraction

Objectives: Keep conveyance free to avoid backups and overland contamination; service inverts without humans in confined spaces.

A) Surface inlets & grates

- **Routine:** daily curb-to-grate sweep (see §4.1); photo of throat; auto-ticket if 2 days obstructed.
- **After storms:** deploy vacuum head; squeegee slurry; curb socks during wet operations.

B) CCTV pipe crawlers

- **Specs:** IP68, pan/tilt/zoom, 100–300 m cable, inclinometer; optional radiation probe.
- **Tasks:** defect coding (NASSCO), joint offsets, roots, debris piles, infiltration.
- **Output:** segment score + clip library; ticket root-cutter or flusher.

C) Root cutting & jetting

- **Root-cutter:** rotary head; push via crawler or boom; torque/load monitored.
- **Jetting:** RO water; pressure & nozzle matched to pipe; capture downstream when feasible.
- **QC:** post-cut CCTV pass; root mass to sealed pans.

D) Vacuum extraction (vactor robot)

- **Use:** silt traps, wet wells, siphon chambers; negative-pressure hood to reduce aerosols.
- **Waste:** dewater to press; cake to drum; liquor to treatment.

E) Wet well/pump station service

- **UGV tasks:** screen rake, rag cutter, float replacement, seal checks; no human entry.
- **Sensors:** H_2S, LEL, O_2 monitors on mast; auto-vent via HEPA blower as needed.

F) KPIs & triggers

- **KPIs:** repeat blockage ≤ 5%; CCTV coverage ≥ 25%/yr grid; SSOs = 0 in pilot; post-storm drain time < 2 h.
- **Teleop triggers:** gas alarms, float failure mid-cycle, unexpected wildlife or trespass.

G) Decon

- High-splash work gets deep-wash recipe; PPE skins for manipulators replaced; sumps polymer-dose tuned for organics.

5.4 Telemetry: permanent dose and flow sensors maintained by bots

Objectives: Replace guesswork with live signals; let robots service, calibrate, and swap sensors without human exposure.

A) Sensor families

- **Dose:** fixed NaI/CZT posts at intersections, plant perimeters, airlocks; integrate with street PM for context.
- **Air:** $PM_{2.5}$/PM_{10}, wind, humidity, temperature at curb height and rooftops.
- **Water:** pressure/flow at DMA (district metered areas), chlorine residual, turbidity, tank levels.
- **Wastewater/storm:** level loggers at critical inverts; rainfall intensity.

B) Installation & service

- **Mounting:** standardized quick mounts reachable by UGV boom; tamper seals; solar + battery or streetlight taps.
- **Service bot tasks:** wipe optics; swap cartridges; calibrate with bottled standards (water) or KCl check (dose).
- **Verification:** before/after calibration photos; test packet QR scanned to log.

C) Data backbone

- **Comms:** private LTE/5G + LoRa for low-rate nodes; store-and-forward if out of coverage.
- **Integrity:** signed packets, time sync via GNSS; edge buffering for 72 h.
- **Open access:** public dashboard: dose map, PM map, water pressure & outages, with confidence bands.

D) Alarms & automations

- **Dose spike:** geofence widen, reroute robots, raise indoor HEPA cadence; dispatch confirmatory UAV.

- **Pressure drop:** leak hunting routine; isolate DMAs via valve bots.
- **Sewer level rise:** pre-emptive grate clearing + downstream vacuum robot stage.
- **Chlorine residual low:** injector skid dispatch; alert kitchens to boil-avoid (use RO instead).

E) KPIs

- Sensor uptime ≥ 99%; calibration drift alarms < 1%/week; mean time to robot service ≤ 24 h; % of events with automated mitigation applied ≥ 95%.

Cross-cutting safeguards for utilities work

- **No human entries outdoors.** Confined spaces served only by bots; if tooling cannot do the job, redesign or shield.
- **RO-only fluid in contact with food/potable systems.** Distinct fittings, color codes, backflow checks.
- **Shields-first doctrine.** Before cutting, place temporary barriers; verify with probe.
- **Chain-of-custody everywhere.** Each intervention produces a work log with photos, torque curves, water quality/dose readings, and decon receipts.
- **Equity routing.** Clinics, schools, and public kitchens are first in line for restorations and patrols.

Bottom line: With the right platforms, end-effectors, wash/decon lines, and live telemetry, a city can maintain power, water, and sewer levels of service **entirely by robot**, keeping human routine exposure at **zero** while raising reliability.

6) Construction, Repair, and Shielding

6.1 Remote site prep: grading, compaction, pallet staging

Objectives: Prepare pads, lanes, and laydown yards without human exposure; deliver consistent subgrade and tidy materials flow that downstream robots can build on.

Fleet & tooling

- **Dozer-bot (tracked, 3–8 t):** 6-way blade, RTK GNSS + LiDAR for grade control (±1.5 cm).
- **Roller-bot:** smooth/vibratory drum with onboard **intelligent compaction** (IMU, modulus estimate).
- **Telehandler-bot:** 2–4 t lift, pallet forks + clamp, 3D obstacle avoidance; pallet tag scanner.
- **Paint/mark bot:** line-chalker for stringlines, bolt grids, exclusion zones.

Workflow

1. **Scan & plan:** UAV photogrammetry → digital terrain model; define cut/fill and geofences; upload to dozer control.
2. **Bulk earthwork:** dozer-bot executes cut/fill in layers; auto-slope around drains; wind triggers blade detune to avoid dust lofting.
3. **Proof & compact:** roller-bot follows with target passes; raises **heat-map** of stiffness; areas < target auto-reworked.
4. **Pallet staging:** telehandler-bot unloads trucks at yard boundary; moves pallets (block, CMU, shields, pipe) to **QR-marked** laydown by construction phase; keeps aisles clear for mules.

QC & KPIs

- Grade tolerance: ±1.5 cm; crossfall ±0.3%.
- Compaction: ≥ 95% of target modulus map green first pass; rework rate < 10%.
- Pallet cycle: truck dock→laydown P95 ≤ 15 min; pallet misplacements < 1%.

Teleop triggers

- Unknown utilities or voids, blade chatter on buried debris, slope failures, bystander intrusion.

Decon

- Low-splash spray + squeegee at yard exit; tracked mud captured to sump → press → drum.

6.2 Robotic construction: mobile 3D printing, brick/CMU tenders, bolt/anchor setting

Objectives: Assemble durable structures—walls, kiosks, shelters, foundations—using robotic methods that minimize dust, splash, and rework.

Tooling

- **Mobile 3D printer (gantry or boom):** prints mortar/concrete layers (low-dust mix, fiber-reinforced); nozzle with skirt to reduce aerosol; inline slump/flow sensor.
- **Block/CMU tender:** vision-guided pick-and-place with thin-bed mortar dispenser; laser line for course check.
- **Fastener base:** 6-DOF arm with **hammer drill**, **chemical anchor injection**, **torque tool**, nailer/stapler; built-in pull-test module.
- **Sealant head:** pump + bead nozzle; thermal seam sealer for film/geomembrane overlaps.

Work instructions (WIs)

WI-A: Printed wall segment

1. **Palletize & mix:** robot mixes RO water + sealed dry blend; QC flow ring.
2. **Print:** 15–20 mm lifts; dwell per layer spec; skirt down; purge path when pausing.
3. **Embed:** robots place conduits/anchors between lifts; QR-tag each embed.
4. **Finish:** trowel bot smooths; vision checks dimensions; cure tent deployed if windy/dry.

WI-B: CMU wall with thin-bed

1. Snap lines by paint-bot; lay starter course on leveled mortar bed.
2. Tender places CMUs using vacuum gripper; thin-bed extruder applies consistent bead.
3. Every N blocks: robot sets vertical rebar + grout injection (low-splash).
4. Pull-test random anchors; capture torque curves.

WI-C: Bolt/anchor setting on slab

1. Scan slab; mark hole grid; drill with vac shroud (dust → HEPA).
2. Blow/brush robot cleans hole; inject 2-part adhesive (lot-logged); set stud; **QR tag**.
3. Cure timer; then torque to spec; log curve to passport.

Controls & safety

- **Dust/particulate:** shrouded tools + HEPA; mist curtains on windy days; zero dry cutting/grinding.
- **Mix water:** RO only; sealed powders; no loose lime handling in wind.
- **Lifts & access:** no human ladders; robot scissor/boom bases with cage sensors.

QC & KPIs

- Dimensional check pass ≥ 98% first-go; void rate in printed walls < 2% by thermal or UT scan.
- Anchor failures in pull-test ≤ 1% (rework immediately).
- Mortar/print batch traceability 100% (lot, water, temp, time).
- Rework hours < 8% of build hours.

Teleop triggers

- Nozzle clog, bead break, block tolerance out-of-range, cure tent lift, chemical anchor temp out of range.

6.3 Shielding: modular lead/steel/water-wall deployment, sandbaggers, temporary shelters around hotspots

Objectives: Rapidly drop dose rates at work spots, routes, and public edges—so other robots can work faster and H-zone risk stays low.

Shield kit

- **Modular panels:** steel/lead sandwiches on dollies (e.g., 50×100 cm, 10–30 mm Pb equiv), tongue-and-groove edges; quick pins.
- **Water walls:** collapsible frames with RO fill; level sensors; drain ports to sump.
- **Sandbagger:** hopper + twin chutes; auto-fill, weigh, tie; palletizer robot for bags.
- **Portable berms/tents:** snap-frame with weighted skirts; geomembrane rolls; magnetic/clamp anchors.
- **Meter mast:** telescoping arm with dose probe for before/after verification.

Deployment playbooks

PB-1: Roadside hotspot barrier

1. **Scout:** UAV spectro heatmap → UGV confirms.
2. **Perimeter:** cones + geofence; paint-bot marks panel line.
3. **Set base mats**; roll in panels; pin; overlap seams; corner keys.
4. **Verify:** meter mast logs pre/post µSv/h; upload to map.
5. **Edge sealing:** sandbag skirts or sealant bead to ground.

PB-2: Work-cell shielding for cut-and-bag

1. **Stage dollies:** two walls + roof lid panels; negative-pressure hood with HEPA hose.
2. **Set walls around pipe/equipment;** lid last; connect hood; verify airflow.
3. **Telemanip cut/shear** inside cell; bag section; wipe; meter check; pass out via small goods lock.
4. **Strike:** reverse with decon; panels through wash line; verify clean.

PB-3: Water-wall for temporary pedestrian route

1. Place frames along path; fill with RO; monitor level; add **gravel socks** at base to prevent splash.
2. Verify dose reduction; add tarp cap if needed for dust.
3. Drain to sump after event; IX polish if required.

PB-4: Large-area tarp & berm for exposed soil

1. Unroll geomembrane with roller-bot; overlap 30 cm; heat-seam; edge sandbag chain.
2. Anchor to kelly bars/earth screws; UAV checks uplift.
3. Perimeter berm built by sandbagger; inspect after wind/gust alarms.

QC & KPIs

- Time-to-shield: roadside barrier ≤ 45 min from ticket; work-cell set ≤ 30 min.
- Dose reduction at 1 m: ≥ 70% (as specified per job) verified and logged.
- Panel seam failures: 0 during mission; water-wall leak rate < 1%/h.
- Tarp uplift incidents: 0 at winds ≤ 12 m/s.

Teleop triggers

- Panel snag near traffic, gusts > 12 m/s, unstable footing, probe excursion (unexpected source strength).

Decon & storage

- Panels/tents through wash line; gaskets inspected and replaced by hours-run; store by **clean/used** rows.
- Water-wall drain liquor to sump → filter/IX; sandbags: keep “dirty” vs “clean” pallets separate; lifed and barcoded.

Data & passports
Every shield set generates a **Shield Passport**:

ticket_id, location, panel_types(count), waterwall_vol_l, sandbags(count),

pre_dose_uSvph, post_dose_uSvph, meter_id, time_on, time_off,

robots_involved, photoset_url, anomalies, decon_receipts

Bottom line: With grade-accurate site prep, dust-smart robotic building, and fast, modular shielding, cities can construct, repair, and work beside hotspots entirely by machine—compressing human exposure to **zero routine hours** while keeping projects on schedule and auditable.

7) Emergency Services

7.1 Firefighting: water/foam drones, ground pump tenders, thermal search, door forcible-entry tools

Objectives: Knock down fires, prevent toxic/dusty smoke migration, and preserve egress—without outdoor human entry.

Fleet & tooling

- **Water/foam UAVs:** 10–25 L belly tanks (quick-swap), nozzle gimbal, thermal + RGB, laser alt for hover holds.
- **Ground pump tenders (UGV):** trailerable high-pressure pumps; hydrant coupling tool, hose reel with **low-aerosol fog** and foam inductors.
- **Thermal search bots:** quadrupeds with pan-tilt thermal, CO/CO_2/HCN sniffers, loudspeaker, IR strobe.

- **Forcible entry base:** 6-DOF arm with hydraulic spreader/cutter, Halligan head, rotary saw (vac shroud), door breacher.

Playbooks

FF-A: Exterior attack (vehicle/bin/brush near structures)

1. UAV thermal size-up → mark heat polygons.
2. Pump tender sets at hydrant (RO rinse post-op), deploys fog nozzle; UAVs foam the windward edge to halt spread.
3. Thermal bots confirm knockdown; perimeter cool-down mist to pin particulates.
4. Post-fire washdown minimal; runoff captured with curb socks → vacuum pan.

FF-B: Structure perimeter defense

1. Thermal scan identifies window/soffit heat; breacher opens targeted vents (saw under shroud).
2. Directed fog through openings; UAV overwatch for roof hot spots.
3. Place temporary **negative-pressure hood** at breach to pull smoke away from H-zone intakes; HEPA truck connection.

FF-C: Door & corridor clearing for rescue robots

1. Breacher spreads/peels door; throw wedge; sweep debris with dozer blade attachment.
2. Thermal bot announces approach (“Stay still—robot assistance”).
3. If interior untenable, deploy small **water-mist curtain** modules in doorway.

SOP & safety

- **Water choice:** potable not required for suppression; **RO for any washdown** near food/airlock paths.
- **Aerosol control:** fog pattern bias; no wide-open streams into dust accumulations.
- **Spark control:** all saws shrouded + on-tool HEPA; foam first, cut second.
- **Comms:** priority channel; automatic geofence to keep other robots clear.

KPIs

- First water on target ≤ **6 min** (P90) within covered districts.

- Rekindle rate ≤ **2%**; smoke at H-zone intakes ≤ target in **30 min**.
- Runoff contained in **≥ 95%** events; curb socks deployed P95 ≤ **4 min**.

Teleop triggers

- Wind gust > 10 m/s at nozzle, structural collapse signs, crowd approach, multiple alarm conditions.

Decon

- Hose/nozzles RO flush; UAV belly tanks through wash line; absorbent booms to drum; filters swapped and logged.

7.2 Hazmat: sample capture, smear tests, hot-spot puck placement, perimeter beacons

Objectives: Characterize unknown materials, enforce space control, and buy time for specialty teams—without human outdoor exposure.

Tooling

- **Sample capture kits:** core tubes, swipe pads, vacuum micro-sampler with sealed cartridges.
- **Smear/Swipe module:** pressure-controlled arm; pre-weighed pads in magazines; auto-bag and label.
- **Hot-spot pucks:** self-adhesive dosimeter nodes (NaI/CZT), BLE/LoRa beacons, LED status ring.
- **Perimeter beacons:** tripod strobes/speakers, QR placards with map link.
- **Mini hot-cell tote:** shielded box on UGV for temporary on-scene containment.

Playbooks

HZ-A: Unknown powder/soil on sidewalk

1. Cone & **soft geofence**; micro-mist perimeter to prevent lofting.
2. **Swipe test** (surface) → sealed bag; **pinch sample** to tube; vacuum micro-sample for fines.
3. Quick NaI screen in mini cell (look for 662 keV vs 1460 keV cues).
4. Place hot-spot puck; set perimeter beacons with audible “Do not cross.”

5. Tote sealed; route to goods/waste lock → lab.

HZ-B: Suspicious package/vehicle residue

1. Thermal + dose check outside line of sight; do **no-touch** sniff (VOC) if safe.
2. Adhesive **lift tape** on seams/handles; swab interior air if open.
3. If dose excursion: deploy **portable shields**, widen perimeter, escalate to specialty removal robot.

HZ-C: Drain/inlet contamination

1. Curb socks first; swab grate & throat; plug (inflatable) if needed.
2. Vacuum head extraction; sample liquor; place puck and log rising/falling trend.

Chain-of-custody (auto-logged)

ticket_id, gps, time, robot_id, sample_id, method(swipe/core/vac),

container_serial, photoset_url, field_screen(cs137/k40/other), puck_id,

perimeter_ids, custody_path

KPIs

- Scene control ≤ **5 min**; first lab-ready sample ≤ **15 min**.
- Data completeness (photos + chain) **= 100%**.
- False evacuations < **1 per 50** incidents (via after-action review).

Teleop triggers

- Public interference, high wind with fines, proximity to ignition sources, dose above robot spec.

Decon

- Tool magazines through wash line; used pads/tubes to yellow drums; mini cell wiped and portal-checked.

7.3 Medical relay: AED/med pack delivery to A-zones; casualty drag sleds (robot-to-airlock)

Objectives: Get lifesaving equipment and extraction capacity to the threshold fast, so humans can treat **inside**.

Fleet & tooling

- **AED/med-pack drones:** 2–5 kg payload, auto-unlock code sent to caller; loudspeaker + two-way audio.
- **Quadruped medic mules:** med panniers (bleed kit, airway, thermal blanket), high-lumens beacon.
- **Drag-sled UGVs:** low-profile sled with soft harness; 150–250 kg pull; obstacle sensors; shock-isolated deck.
- **Airlock stretcher dock:** height-matched rollers; “dirty-side” vestibule with negative pressure.

Playbooks

MED-A: AED to bystander

1. Dispatch nearest drone; ETA and unlock PIN texted to caller.
2. Drone instructs via speaker; strobe marks landing.
3. Quadruped mule follows with additional kit if within 600 m; provides lighting and scene marking.

MED-B: Casualty to airlock

1. Thermal/search bot locates person; loudspeaker instructions; assesses egress path.
2. Drag-sled bot positions, lowers harness; guided by camera to avoid head/limb snag.
3. Route to **designated medical airlock** (shortest, smoothest); ping clinicians to meet inside.
4. At lock: exterior wipe of sled; inner team receives casualty through rollers; sled remains in vestibule until decon finish.

MED-C: Multi-casualty / smoke corridor

1. Deploy **mist curtains** at corridor ends (low-aerosol) to limit smoke/dust.
2. Two sleds leapfrog; drones drop extra airways/bleed kits at intersections.

SOP & safety

- **Scope:** robots do **movement and kit delivery**, not invasive care.
- **Communication:** live audio uplink to 911/clinic; multilingual prompts; privacy mask on video streams saved to record.
- **Ergonomics:** max slope/camber tables; “slow zones” over rough patches; avoid stairs unless sled lift is fitted.

KPIs

- AED on scene ≤ **5 min** (P90) in covered grid.
- Robot-to-airlock transfer ≤ **10 min** for 500 m radius incidents.
- Sled re-injury (contact bumps, tip) **= 0**; after-action satisfaction ≥ **90%**.

Teleop triggers

- Victim entanglement, bystander interference, narrow passage < sled width + 20 cm, visibility < 2 m.

Decon

- Sleds: deep-wash recipe; harness laundering; portal verify.
- Med packs: outer wipe; restock from sealed lots; AED pads/batteries lot-logged.

Cross-cutting threads for Emergency Services

- **No human outdoor entry.** If a task demands hands, deploy telemanip through shields or redesign the tool.
- **Aerosol discipline:** fog > stream; shrouds on cutters; curb socks on wet work.
- **Evidence & transparency:** every incident produces a public log (redacted where needed) with photos, timings, and mitigation summaries.
- **Equity:** response-time SLOs published by zip; clinics/schools/public kitchens get priority routes.
- **Training:** quarterly indoor drills with live teleop practice; citizen 30-minute course on AED drone handoff and medical-airlock etiquette.

Bottom line: Robots make fire, hazmat, and rescue **threshold tasks**—bringing suppression, characterization, and patients to the door—so people can stay safe inside while lifesaving work still happens on time.

8) Waste, Recycling, and Logistics

8.1 Household waste: sealed smart bins → robot pickup → compaction/classification

Objectives: Remove household waste without outdoor human contact; prevent dust/aerosol release; keep "yellow-stream" (potentially contaminated) materials segregated.

Smart bin design (H-zone interior)

- **Form factor:** 120 L & 240 L carts, foot-pedal lid, gasketed rim, auto-latch.
- **Sensors:** weight cell, lid-open counter, fill % (ultrasonic), bin temp, tamper switch.
- **Tags:** QR/NFC with **stream code** (general / organics / recycling / "yellow").
- **Consumables:** color-coded liners; cinch ring captures liner edge under lid.

Pickup workflow (UGV mule)

1. **Signal & schedule:** Bin reaches threshold (e.g., 80%) → **slot offered** via hallway panel; or fixed-route pickup.
2. **Airlock handoff:** Resident pushes to **waste lock**; lock scans bin ID, weighs, photographs; quick **air-knife** and **gamma sniff** for "yellow" candidates.
3. **Curb robot bay:** UGV clamps bin, tips to sealed hopper; **negative-pressure shroud** and HEPA on during tip.
4. **Classification:** Inline vision checks liner color, rejects cross-stream; "yellow" flagged to separate hopper.
5. **Receipt:** Resident receives **pickup ticket** (weight, photo, stream result, ETA to MRF/transfer).

Depot processing

- **General/Recycling:** compactor with **mist suppression**; bales or transfers to MRF in covered roll-offs.
- **Organics:** sealed digesters/containers; no open windrows.

- **“Yellow” stream: shielded compactor**, drums or lined boxes; barcode to pallet slot in **shielded rack**.

SOP guardrails

- No loose bags outside locks.
- If gamma gate alarms → auto-reroute to “yellow” lane; notify resident with neutral language and next steps.

KPIs

- Pickup latency P90 ≤ **24 h** after threshold ping (≤ **12 h** for clinics/schools).
- Bin mis-sort rate ≤ **2%**; cross-stream contamination ≤ **1%** by audit.
- Hopper fugitive PM below floor target; compactor HEPA ΔP in range.
- Equity: variance of pickup latency across zip codes ≤ **2×** median.

Teleop triggers

- Obstructed bays, animal interference, overflowing bins, repeated cross-stream flags.

Decon

- Bin exteriors wiped in-lock; robot grippers through wash line; hopper wash to sump → filter press → drum for fines.

8.2 Industrial/robot filters: cassette swaps, barcode tracking, shielded storage

Scope: HEPA cassettes (street sweepers, airlocks), IX cartridges (water polish), portal prefilters, robot shrouds/skins—**anything that accumulates dust or radionuclide load**.

Inventory & ID

- Every consumable is a **lot-tracked asset**:
  asset_id, type(HEPA/IX/prefilter/skin), size, vendor_lot, in_service_at, hours_run, ΔP_history, gamma_gate_result, out_service_at, storage_slot

Swap workflow

1. **Trigger:** ΔP or hours-run threshold; or scheduled PM.
2. **Hot swap cell (garage dirty lane):** doors interlocked, negative pressure; manipulator unlatches cassette; auto-cap both ends; bag-and-tape; barcode print.

3. **Gamma gate:** 60–120 s count; if below criteria → “general filters.” If above or unknown → **“yellow filters.”**
4. **Weigh & store:** tote to shielded rack by activity band; FIFO for outbound to licensed processor.

IX cartridges

- **Conductivity gate:** swap when permeate creeps ≥ 10 ppm over baseline or age limit.
- **Handling:** drain to closed pan; cap; barcode; gate check; store in compatible drum.

Audit & reconciliation

- Weekly: **filters-in vs hours-run** sanity check; random swipe on “general filters” pallet to confirm classification.

KPIs

- On-time swaps ≥ **98%**; missing asset records **= 0**.
- “Yellow” storage utilization ≤ **85%** (capacity margin).
- Worker indoor dose trend flat; garage portal alarms investigated within **24 h**.

Teleop triggers

- Torn bag, cassette latch mis-seat, portal excursion, rack near capacity.

Decon

- Swap cell wiped and portal-checked between batches; tools through wash line; spill kits staged.

8.3 Deliveries: tote routing, roof lockers, curb lockers, proof-of-decon and dose ticket

Goal: Move goods **from R-zone to H-zone** without human outdoor handling, with proof that each tote crossed a measured, auditable hygiene boundary.

Locker types

- **Roof lockers:** UAV/roof-mule accessed; weather hood; passive RF tag reader; motorized chute to interior vestibule.
- **Curb lockers:** UGV height; dual doors (outside/inside) with **interlock**; built-in **mini air-knife + mist + gamma gate** for small parcels.

- **Bulk docks:** pallet-size goods locks (see §2.3).

Routing & prioritization

- **Tote passport** created at origin: tote_id, source, lot_ids, weight, temp(if cold), chain_step.
- Optimizer batches totes by address, **A-zone availability**, perishability, and equity quotas (schools/clinics first).

Delivery cycle

1. **Origin seal:** producer robot seals food-grade liner; prints passport QR; takes photo.
2. **Outbound decon:** robot wash → decon gate at depot; passport updated "clean outbound."
3. **Transport:** UGV mule or UAV to assigned locker; ETA shared to recipient.
4. **Locker cycle:** air-knife 45–60 s → mist 60–90 s → **gamma count 60–120 s** (geometry posted) → decision.
5. **Release:** H-side door unlocks; recipient retrieves; **dose ticket** prints/appears in app:
6. delivery_id, tote_id, gamma_count_s, mda_cs137_bqkg, peaks_found,
7. decon_recipe, photoset_url, decision, time
8. **Exceptions:** "Hold" → tote parks in locker quarantine; lab pickup ticket auto-generated.

Special cases

- **Meds/biologics:** cold chain logger; lock gives **thermal strip** read; priority routing; dual verification on release.
- **Cash-poor households:** "Anytime" curb locker hours + printed receipts; no app required.

KPIs

- First-pass release ≥ **99.5%**; P90 delivery latency ≤ **4 h** from depot handoff (≤ **2 h** for clinics/schools).
- Quarantine resolution ≤ **24 h** average; locker uptime ≥ **99%**; equity variance (latency spread) ≤ **2×** median.

Teleop triggers

- Locker jam, rain splash intrusion, repeated portal "holds," wildlife interference.

Decon & maintenance

- Lockers run self-sanitation cycles nightly; filters checked weekly; seals/gaskets lifed.
- Drone pads and curb aprons sticky-rolled daily; spill kits at curb lockers.

Shared data, custody, and equity controls (for §8)

Unified event schema

event_id, ts, gps, actor(robot_id/locker_id), flow(waste/delivery/filter),

item_id, stream_or_tote, weight, photoset_url, gamma_gate_s, mda_cs137_bqkg,

decision(release/hold/reject), next_hop, operator_id(optional), notes

Public dashboards

- **Waste:** pickups by zip, mis-sort rate, “yellow” tonnage (privacy-preserving).
- **Filters:** swap compliance, storage capacity, outbound manifests.
- **Deliveries:** on-time rate, quarantine counts, equity latency bands.

Governance

- Contracts require **raw logs & photos** export; no “cleanliness scores” without evidence.
- **Appeal path**: residents can request a re-gate within 24 h; independent lab available for contested lots.
- **Accessibility:** lockers support PIN + QR + physical code; paper tickets for households without smartphones.

Bottom line: With sealed smart bins, cassette-savvy depots, and proof-of-decon lockers, cities convert messy, dose-amplifying flows into **sealed, logged, and auditable** logistics—keeping routine human exposure at **zero** while services stay fair, fast, and predictable.

9) Building & Roof Service

9.1 Roof vacuuming, gutter purge, PV wash and swap

Objectives: Keep roofs from re-lofting dust, prevent gutter overflows that redeposit fines, and maintain PV output—no human outdoor work.

Fleet & tooling

- **Roof mules (UGV):** low-CG, tetherable; HEPA vacuum head with ΔP sensor; squeegee bar; debris pan.
- **Gutter crawlers:** tracked minis with narrow **HEPA vac wand**, squeegee fin, camera nose.
- **PV wash boom:** squeegee bar + RO spray; inline conductivity interlock (< 30–40 µS/cm); soft bristle head.
- **Panel swap rig:** telehandler-bot with vacuum lifter, torque head, MC4/connector tool kit.

Playbooks

R-1 Roof vacuum loop

1. UAV survey tags dust accumulations & loose ballast; set geofence and roof entry.
2. Mule runs **perimeter → field → parapet** serpentine; ΔP automates brush height.
3. Edge push: dust toward staging mats; vac to sealed pan; photo each quadrant "after."
4. Portal check at roof hatch; pan to waste lock.

R-2 Gutter purge

1. Crawler launches at scupper; **vac → squeegee → vac** sequence every 2–3 m.
2. Downspout test with flow puck; flag if < threshold; deploy jet head if needed (RO water only).
3. Snap "clean grate" photo; update GIS.

R-3 PV wash & swap

- **Wash:** RO mist + squeegee; wind < 7 m/s; no soaps unless vendor-approved; conductivity alarm = pause.
- **Swap:** isolate string; telehandler aligns vacuum lifter; remove panel; cap connectors; lay new panel; torque per spec; thermal scan & IV curve check.

KPIs

- Roof dust mass removed/1000 m^2; re-loft PM reduction ≥ **30%** week-over-week.
- % gutters with verified flow **= 100%** post-route; repeat blockages ≤ **5%**/month.
- PV: output restored ≥ **95%** of nameplate (irradiance-normalized); swap cycle P95 ≤ **25 min/panel**.

Teleop triggers

- Wind gusts, parapet defects, skylight edge proximity, ΔP spike (clog), panel connector damage.

Decon

- Vacuum heads through wash line; pans sealed to waste lock; roof mule tires/track pads wiped at hatch; squeegee bars RO-rinsed.

9.2 Facade tasks: squeegee booms, crack sealing, air intake filter swaps (outside side)

Objectives: Keep vertical surfaces from shedding dust, prevent water intrusion, and protect HVAC intakes—all via robots.

Fleet & tooling

- **Squeegee boom bots:** mast climbers or cable-tethered platforms with RO spray + squeegee head, edge brushes.
- **Sealant rigs:** 6-DOF arm with crack-chaser (vac shroud), backer rod feeder, sealant bead nozzle, thermal seam sealer for membranes.
- **Intake service bots:** compact platform with quick-release filter frame tool, ΔP probe, gasket kit, lint roll head.

Playbooks

F-1 Facade wash (low-aerosol)

1. Map windows/bays; plan drops; RO mist (no fan jets); squeegee bottom-up to avoid streaks; edge brush at sills.
2. Photo after each bay; runoff captured in gutter socks at drip lines where feasible.

F-2 Crack seal

1. Vision detects crack geometry; crack-chaser with HEPA shroud tracks; dust to sealed canister.
2. Backer rod insertion robot; apply bead; tool profile; thermal/IR quick check for voids.
3. Cure tag (timestamp + lot); photo log.

F-3 Air-intake filter swap (outside face)

1. ΔP across intake measured; if ≥ threshold or age-out: open grill; remove spent prefilter to bag; wipe frame; seat new prefilter/HEPA; verify ΔP drop; gasket inspect.
2. Spray/wipe intake surround; photo “clean ring.”

KPIs

- Facade re-soiling interval extended ≥ **2×** vs baseline; dust fall on sills ↓ **≥ 40%**.
- Sealant rework ≤ **3%**; water-ingress tickets from sealed bays **= 0** after storms.
- Intake ΔP normalization on swap **≥ 90%** cases; surprise swab positives **< 1%**.

Teleop triggers

- Wind > 10 m/s on mast; loose facade elements; passerby proximity; abnormal ΔP (blocked intake).

Decon

- Crack-chaser cans to filter press; squeegee heads RO-rinsed; intake frames wiped; spent filters handled per §8.2 (barcode → rack).

9.3 Antenna/5G repairs: mast climbs, connector torquing, spectrum checks

Objectives: Maintain rooftop/streetscape radios without humans outdoors; avoid loose hardware becoming debris; minimize RF downtime.

Fleet & tooling

- **Mast climbers:** tracked/roller minis with fall-arrest tethers; 6-DOF arm.
- **Connector kit:** calibrated torque driver, dielectric grease dispenser, weather-boot installer, label printer.
- **Spectrum cart:** SDR + calibrated antenna, GPSDO, analyzer for VSWR/return loss.
- **Cable bots:** conduit snakes to pull or trace coax/fiber; OTDR for fiber tests.

Playbooks

A-1 Routine torque & inspect

1. UAV visual pre-pass; mast climber ascends; checks bracket bolts; torques to spec with logged curve.

2. Inspect connectors; re-seat/grease; install new weather boots if cracked.
3. Label/QR update; photo set saved.

A-2 Connector/cable fault

1. Spectrum cart baseline sweep → suspect sector flagged.
2. VSWR high? Arm reseats; if still high, cable bot OTDR/fault distance; swap jumper; if feeder, pull new.
3. Post-repair sweep; compare to template; close ticket.

A-3 Antenna swap or tilt/azimuth adjust

1. Lockout on sector; arm loosens clamps; swap panel; torque; set tilt/azimuth from plan; verify with network KPI bump.
2. Weather window constraints enforced; wind < 8 m/s.

KPIs

- Trouble ticket MTTR ≤ **4 h**; torque curve logs **100%** captured; post-work VSWR ≤ spec in **99%** cases.
- Stray hardware incidents **= 0**; weather-boot failures **< 1%/quarter**.

Teleop triggers

- Lightning proximity, high gusts, ice accretion, unexpected RF emission anomalies.

Decon & RF hygiene

- Tools wiped; boots/bands bagged if dusty; mast climber treads wiped at hatch.
- RF exposure kept below limits: robots observe exclusion zones; human operators remain inside—visuals only.

Cross-cutting guardrails for §9

- **RO water for any wash process** touching surfaces with runoff toward H-zones or food paths.
- **Aerosol discipline:** mist + squeegee, shrouds on cutting/grinding; curb socks at downspouts during heavy washing.

- **Edge safety:** geofences along parapets; automatic “roost/brace” on gusts; UAV buddy checks before moves.
- **Chain-of-custody:** photos, torque curves, ΔP/IV curves, and waste receipts attach to a **Building Service Passport** per task.

Bottom line: A dedicated roof/facade service fleet keeps dust down, water out, and power/data stable—quietly, on schedule, and **without a single outdoor human step**.

10) Tooling, Autonomy, and Teleop Triggers

10.1 End-effectors library: grippers, shears, saws, nut-runners, vac heads, sprayers, seeders

Quick-change spine (common to all robots)

- **ISO tool plate** with power (24/48 VDC), pneumatics, RO-water quick-fit, and data (EtherCAT/CAN).
- **EEPROM tool tag** exposes: tool type, max force/torque, compatible RPM/flow, calibration date, serial, hours-run.
- **Auto-handshake:** robot loads tool limits, hazards, and inspection prompts before enabling motion.

Core tools & spec snippets

- **Parallel gripper (soft pads):** 0–120 mm, 80–150 N; slip sensing; food-grade skins for totes/produce.
- **Vacuum gripper (panel/CMU/panel PV):** 1–4 cups; vacuum integrity test < 2 s; auto de-sand before lift.
- **Shears (cable/branch):** 10–25 mm capacity; interlocked guard; force feedback for “hard-stop” detect.
- **Reciprocating/rotary saw (shrouded):** on-tool HEPA; spark arrestor; RPM auto-throttle by load.
- **Nut-runner/torque head:** 5–150 N·m; closed-loop torque/angle; **torque curve** saved per fastener.
- **Core sampler (soil/pipe):** 8–25 mm; sleeve liners; cap both ends on retract; barcode sleeves.
- **Vacuum head (street/roof/gutter):** ΔP sensor; skirted lips; quick swap bags/cassettes.

- **Squeegee skid:** downforce control; perimeter lip; anti-trail lift at end of stroke.
- **Sprayer wand (inside covers):** electrostatic nozzles; RO feed; deposition cards & camera readback.
- **Seeder (vac singulation):** plate cassettes by seed size; hopper weight cell; seed proof-of-drop counter.
- **Thermal/steam weed lance:** 300–400 °C or 100 °C steam; shroud to prevent lofted fines.
- **Sealant pump/nozzle:** 2-part mix, bead camera; cure timers; lot tracking.
- **Lift/drag sled coupler:** soft-start pull profile; shock isolation; vitals overlay for teleop.

Maintenance & QA (per swap or per shift)

- 6-point visual, pad wear, filter ΔP, vacuum leak test, torque tool calibration check, sprayer flow/EC test.
- Log entry: tool_id, hours_run, check_pass(bool), parts_replaced[], next_due_ts.

10.2 Autonomy: route follow, change detection, adaptive tasking; when to hand over to teleop

Behavior tiers (all robots advertise current tier on UI)

1. **Route-follow** (deterministic): GNSS/SLAM path with speed caps, curb-hugging, door/gate states.
2. **Supervised autonomy** (reactive): obstacle negotiation, pause/plan, micro-re-routes; operator can “nudge”.
3. **Adaptive tasking** (goal-seeking): actively chooses next cells/samples to reduce uncertainty (e.g., dose heatmap, PM spikes, missed seeds).
4. **Teleoperation** (direct control): joystick/VR with latency guard; robot enforces safe limits.

Change detection modules (examples)

- **Vision:** debris types, cracks, spills, open lids, animals, bystanders within 1.5 m, door states.
- **Radiation/air:** Cs-137 line presence at 662 keV vs K-40; $PM_{2.5}$ deltas; wind gusts via anemometer.
- **Mechanics:** wheel slip, ΔP spikes, torque anomalies, vacuum loss, nozzle clog signatures.

Adaptive policies (sketch)

- **Street hygiene:** prioritize cells with highest PM residual or recent deposition; increase dwell near inlets with repeated clogs.
- **Spectro mapping: next-best-view** algorithm balances count-time vs coverage; extend dwell where MDA above target; revisit cells with conflicting spectra.
- **Agriculture:** re-seed where emergence vision < threshold; schedule emitter flush when flow variance > x%.

Hand-over to teleop — crisp triggers

- **Geometry:** gap < (robot width + 20 cm), stair not rated, parapet proximity < 40 cm without tether.
- **Physics:** torque/force > 1.2× tool spec; vacuum loss > 30% for > 3 s; ΔP "red."
- **Env:** wind > limit for task; visibility < 2 m; dose rate > robot design limit; liquid sheen near storm inlet.
- **Social:** person/pet within geofence; crowd motion toward robot; law-enforcement scene tape.
- **Semantics:** unknown object class in work envelope; spectral anomaly outside trained classes.

Operator UX (low-friction)

- One-key **"Take Over"**; haptic notch at force/torque limit; overlay of safe envelope; **snap-back** to autonomy on button-up.
- **Recipe cards** per task: "Harvest-under-film," "Valve-leak," "Shield-and-cut"—autonomy preconfigures tools, limits, lighting.

Autonomy health metrics

- % missions fully autonomous; **handover rate** per task; mean teleop duration; false-positive/negative change-detect; rework due to autonomy < 5%.

10.3 Safety envelopes, geofences, and failover behaviors (return/roost/tether)

Safety envelope (per task)

- **Hard limits:** max speed/force/torque/RPM; no-go zones; minimum standoff to edges/intakes/live gear.
- **Soft limits:** approach speeds, tool warm-up windows, “slow zones” (schools/clinics), weather caps.
- **Dynamic pad:** envelope inflates with wind gusts, shrinks in sheltered alleys; expands around bystanders.

Geofences (stacked)

- **City fence:** R-zone bounds; H-zone absolute no-go.
- **Job fence:** worksite polygon + “dirty buffer.”
- **Micro-fence:** active around tool tip; grows when uncertainty ↑ (e.g., SLAM quality ↓).
- **Beacon/QR anchors:** temporary cones/tags create pop-up keep-out or corridors during incidents.

Failovers (deterministic state machine)

- **Link loss:**
  - *Tier 1* (≤2 s): hold position, raise mast light, retry multi-radio.
  - *Tier 2* (2–30 s): reverse 1 m, safe park; UAV climbs to safe altitude & **roosts**.
  - *Tier 3* (>30 s): return-to-home (RTH) via last known corridor; if blocked, **dead-man** (shutdown posture).
- **Power low:** compute remaining route; if < reserve → abort task → RTH; for UAV, **battery hot-swap nest** selection by wind.
- **Sensor stale/failed:** drop to slower **guardian mode** (bumper, basic lidar); request teleop; halt if confidence < threshold.
- **Dose excursion:** stop, back 3 m, drop cone/beacon, push alert, widen geofence; wait for shield job ticket.
- **Weather trip:** wind/rain/icing over limit → safe stow tools, roost/dock, post ETA.

Tethers & catches

- Roof/edge work uses **smart tethers** (load cell + reel); tension alarms pause motion.
- Quadrupeds on stairs use **belly catch straps**; UGV boom work uses **outriggers** with load cells.

Collision & contact policy

- Multi-sensor fusion (LiDAR + vision + bump) with **no-push** default on ambiguous contacts; force caps at skin level; retreat & replan.

Logging & audit (safety-first)

- Every envelope breach attempt → event with 10 s pre/post video, tool data, operator ID (if teleop).
- Schema:
- evt_id, ts, robot_id, task, fence_type(city/job/micro), reason(change_detect/link/power/dose),
- action(hold/rth/roost/deadman), duration, human_takeover(bool), outcome(success/fail), notes

Testing & drills

- Weekly **failover drills** (link-loss, power-brownout, mock crowd); quarterly **wind-gust** validation at test pad; annual **dose-excursion** tabletop with shield team.

Human override policy

- No "step-outside rescues." If a task **requires** a person outdoors, task is **redesigned** (tool, shield, or telemanip through a wall).

Bottom line: A standardized tool library, autonomy that knows when to ask for help, and hard-edged safety envelopes with predictable failovers let robots do messy outdoor work **reliably and auditably**—while people stay comfortably inside.

11) Work Instructions (WIs) & SOPs (examples)

11.1 "Harvest-under-film WI": pick → tote → wash → decon → A-zone release

Purpose. Remove produce from covered beds with **zero human outdoor exposure**, maintaining lot integrity and minimizing dust transfer.

Tools & prep

- UGV harvester with **scissor gripper** (force control), NIR/RGB grader, inline **weigh cell**.
- Food-grade **totes + liners** (QR pre-printed), RO spray tunnel, field **robot wash** pad, pallet mule.
- Goods airlock (see §2.3) with **air-knife + mist + gamma gate**.

Steps

1. **Check-in & sanitize (00:02)**
    - Harvester passes portal, loads “Harvest-under-film” recipe, verifies tool hours/ΔP.
    - Scan bed ID; pull latest fert/spray log to passport.
2. **Open & enter (00:03)**
    - Crack end flap; mist **inside** edge lightly to pin dust.
    - Insert with **service sleeve**; confirm canopy pressure neutral (no wind billow).
3. **Pick & grade (active)**
    - Target fruit/leaf with vision; **grip @ 8–12 N**, cut; place on grader.
    - Reject tray for defects; **log weight** per pick; accumulate by tote.
4. **Tote fill & seal (each tote ~10–15 kg)**
    - Auto-line tote; drop product; **photo top layer**; heat-seal liner or apply tamper tag; lid on.
    - **Print passport** & QR: {tote_id, bed_id, robot_id, start/stop, weight, photo_url}.
5. **Pre-rinse (if dusty crop)**
    - RO spray tunnel **≤ 30 s**; never recirculate; drip **60–90 s** on clean rack.
6. **Robot decon**
    - Air-knife 60 s → mist 90 s → squeegee → portal check.
    - Swap sticky roller if ΔP high.
7. **A-zone release**
    - Tote → Goods Lock → air-knife 45–60 s → mist 60–90 s → **gamma 60–120 s**.
    - Decision: **Release / Hold / Reject**. “Hold” racks to co-op NaI count (60–240 min).

QC & acceptance

- Tote **first-pass release ≥ 99.5%**.
- Grader accuracy ≥ 95% vs human audit sample.
- Residual moisture < 1% by mass (avoid spoilage).
- Photo & weight present for **100%** totes.

Data record (append to passport)

harvest_id, bed_id, crop, tote_id, weight_kg, picks_count,

pre_rinse(sec), robot_wash_recipe, gamma_count_s, mda_cs137_bqkg,

decision, photoset_url, anomalies

Exceptions

- Film tear > 15 cm → Auto-patch routine, then resume.
- Gamma "K-rich" note (1460 keV only) → Release with comment.

11.2 "Valve-leak WI": UAV confirm → crawler assess → clamp and verify → log

Purpose. Diagnose and stop distribution main leaks **without outdoor crews**.

Tools & prep

- **UAV thermal** (dawn/dusk), ground **acoustic kit**, wheeled UGV with **torque head**, clamp kit, vac wand, RO hose, **portable shields**.

Steps

1. **Ticket intake (00:01)**
    - DMA pressure drop alert or citizen report → auto-spawn job polygon.
2. **UAV confirm (00:10)**
    - Thermal sweep; mark cold/wet anomalies; street-wetness vision; push likely point(s).
3. **Crawler assess (00:15)**
    - UGV vacs valve box; **acoustic correlation** at adjacent valves; pick peak cross-corr.
    - Chloride strip on puddles (treated water?) → log reading.

4. **Isolate & prep (00:10)**
    - Place **portable shields** if dose hot; set cones/geofence; sandbag perimeter to prevent run-off.
    - Partial close upstream/downstream valves per model to reduce pressure (teleop confirm torque curve).
5. **Clamp install (00:25)**
    - Saw expose (shrouded; vac on); dewater with vac; clean pipe; wrap clamp; **torque pattern** to spec; dwell 2 min; retorque.
6. **Verify (00:10)**
    - Pressure rise check; no visible weep; acoustic quiets **> 10 dB** vs pre-clamp.
    - RO rinse area; capture before/after photos.
7. **Restore & clean (00:08)**
    - Gradual valve reopen to target; remove sandbags; vac residual; portal wash tools.

QC & acceptance

- **Leak sound reduced ≥ 10 dB** and visual weep = 0.
- Pressure at downstream sensor within **±5%** of setpoint.
- Torque curve stored for all fasteners.

Data record

work_id, gps, valves_touched[], torque_curves_url, pre/post_acoustic_db,

chloride_ppm, partial_isolation(bool), clamp_type, restore_time,

photoset_url, waste_mass_kg, shield_passport_id

Exceptions

- Sinkhole/void → abort clamp; deploy barriers; escalate to cut-out plan.
- Valve torque > limit → stop; mark for replacement job.

11.3 “Shield-and-cut WI”: deploy portable shield → shear pipe → bag section → stage for hot-cell

Purpose. Perform **hot mechanical separations** (pipes/ducts/racks) with temporary shielding and contained bag-out, keeping dose and debris controlled.

Tools & prep

- UGV **shield cart** (lead/steel panels + roof), negative-pressure **hood** with HEPA, **dose probe mast**, 6-DOF arm with **recip saw** (shroud), **bagging ring** & poly sleeves, **tie-off tool**, wipe sampler, **drum dolly**.

Steps

1. **Survey & plan (00:08)**
    - UAV/UGV dose sweep; set shield line on paint; compute expected attenuation; pick panel count.
2. **Deploy shield (00:12)**
    - Lay base mats; roll panels; **pin & key seams**; place roof; verify with probe: target **≥ 70% dose drop** at 1 m.
3. **Set hood & negative (00:05)**
    - Connect HEPA to hood; verify airflow (flow vane in green); smoke test leak paths.
4. **Wipe baseline (00:03)**
    - Pre-cut smear for records; bag and QR.
5. **Bag-and-shear (00:12)**
    - Install **bagging ring** around cut site; slide bag sleeve over pipe; cinch proximal tie; start saw (on-tool HEPA).
    - **Shear/cut** segment; lower into bag; **distal tie**; **proximal wipe**; third tie; cut bag free.
    - Apply **end cap** or temporary plug; wipe again.
6. **Meter & stage (00:05)**
    - Probe bag; label activity band; load to **drum** with dolly; seal; barcode.
7. **Strike & decon (00:10)**

    - Hood off; panel wipe; roll shields to wash pad; portal check; site vacuum of fines; cones remain until **post-cut dose** recorded.

QC & acceptance

- **Attenuation achieved ≥ 70%** (or job spec).
- Bag seals ×3 verified; wipe after cut ≤ site criterion.
- Saw shroud ΔP in range; no visible fines outside hood.

Data record (Shield Passport + Cut Log)

ticket_id, location, panel_count, hood_flow_lps, pre_dose_uSvph, post_dose_uSvph,

tool_id, cut_time, bag_id, wipe_results, drum_id, photoset_url, anomalies

Exceptions

- Probe excursion (> planned source) → pause; add panels; reassess.
- Bag tear → secondary bag procedure; re-wipe; re-meter.

Shared SOP guardrails (for all WIs)

- **Monodirectional hygiene:** dirty → clean; never reverse flow through locks.
- **RO water for any rinse** touching goods/food paths.
- **Aerosol discipline:** shrouds, fog > stream, curb socks on wet work.
- **Teleop triggers are crisp:** wind/visibility/dose/social thresholds drop autonomy to teleop.
- **Chain-of-custody:** every WI emits a **passport/log** with photos, times, tool IDs, decisions, and decon receipts.
- **Equity knobs:** priority queues favor clinics, schools, and public kitchens automatically.

Bottom line: These WIs turn complex outdoor jobs into **repeatable recipes**—tight steps, measurable checkpoints, and clear pass/fail criteria—so robots can do the work reliably while people stay safe inside.

12) Decon & Maintenance

12.1 Robot wash trains: air-knife, mist, squeegee, verify; cassette filters and sludge drums

Purpose. Remove dust and residues from returning robots/tools; capture particulates/liquor; verify cleanliness before any “clean-side” contact.

Line layout (dirty → clean)

1. **Staging mat (ID & triage).** Scan robot/tool IDs; import mission logs; choose recipe: *Standard*, *Deep*, or *Splash/Hazmat*.
2. **Air-knife bay.** High-velocity laminar curtains knock down loose fines into **local HEPA capture** (H14; ΔP monitored).
3. **Mist bay.** Low-splash RO/IX spray with optional chelator; flow interlock if conductivity > 40 µS/cm.
4. **Squeegee rollers.** Adjustable downforce; perimeter lips; reclaim to sump.
5. **Final RO rinse.** Conductivity gate ensures food-path compatibility.
6. **Drip & dry.** 60–120 s; heated makeup air; drip pans plumbed to sump.
7. **Verification portal.** Gamma gate (60–120 s count) + vision (residue, crevice check) + ΔP snapshot for tool heads.
8. **Release flap.** Green → clean lane; Yellow → recirculate; Red → hot-cell.

Standard recipes (guideline times)

- *Standard:* Air-knife 60 s → Mist 90 s → Squeegee 2 passes → Rinse 30 s → Verify.
- *Deep:* Air-knife 90 s → Mist w/ detergent 120 s → Brush head pass → Squeegee 3 → Rinse 60 s → Verify ×2.
- *Splash/Hazmat:* Add enclosure hood; double squeegee; tool decouple & separate line; mandatory hot-cell review if portal alarms.

Liquor & fines capture

- **Sump chain:** Coarse basket → 5 µm bag filter → 1 µm bag filter → **IX polish** → discharge/reuse.
- **Filter press:** Periodic press of 5/1 µm bags & floor fines; cakes → **yellow drums** with barcode & weight.

- **Cassette filters:** Air-knife & local HEPA cassettes tracked as assets (see §8.2) with hours-run and ΔP history.

Instrumentation & interlocks

- Conductivity meters (in/out), ΔP sensors, flow switches, door interlocks, negative-pressure setpoint for mist bay.
- **Abort** if: HEPA ΔP > red; sump level high; conductivity out-of-spec; portal detector fault.

KPIs

- First-pass **clean release ≥ 98%**; recirculation < 2%.
- Liquor recycle fraction ≥ 80% (post-IX); unexpected portal alarms < 0.5% of cycles.
- Mean wash cycle (Standard) **≤ 6 min** P95.

Records (per cycle)

wash_id, ts, robot_or_tool_id, recipe, airknife_s, mist_s, squeegee_passes,

rinse_s, gamma_count_s, mda_cs137_bqkg, decision(release/recirc/hotcell),

bagfilter_dp_in/out, sump_volume_l, operator_id(optional), photoset_url, notes

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12.2 Garage MRO: PM cycles, sacrificial skins, battery/fuel swaps, sensor calibration

Goal. Keep fleet availability high without outdoor labor; catch drift/fatigue before failure.

Preventive maintenance (PM) cadence

- **Every run (post-wash):** visual 6-point; fasteners witness marks; tire/track wear; tool quick-check (vac leak, torque wrench self-test).
- **25 h run-time:** belts/chains tension; cooling fan clean; firmware health; battery health report; sensor lens clean.
- **100 h:** gear oil check; motor bearing temp trend; suspension bushings; replace **sacrificial skins** (clip-on shrouds for dirty jobs).
- **Quarterly:** full drivetrain inspection; encoder & IMU calibration; UAV prop balance; parachute/recovery system test.
- **Annually:** major teardown; seal replacements; structural NDT on hard-use frames.

Energy swaps

- **Battery farm:** BMS-networked racks; SOC, internal resistance, temp; charge/buffer on isolated circuits; hot-swap trolleys.
- **Fuel (if hybrid):** sealed cages for H_2/propane; sniffers; quick-disconnects; spill berm; purge lines.

Calibration program

- **Radiation:** NaI/CZT energy cal (KCl jar) weekly; efficiency check monthly with check source (where licensed).
- **Force/torque:** weekly torque wrench cert (reference transducer); gripper squeeze cell.
- **Vision/LiDAR:** AprilTags board & checker; LiDAR–camera extrinsic solve monthly; lens focus check.
- **Flow/pressure:** sprayer EC/pH two-point; pump flow vs PWM curve quarterly.

Spare parts & consumables

- **Kitting:** job-ready kits (sweep head, sealant set, clamp set, nozzle set) with min/max stock; **kanban** cards trigger orders.
- **Lifed parts:** gaskets, HEPA cassettes, skins, tires/track pads; shelf-life tracked by barcode.

MRO work orders (inside benches)

- Clean-bench only; ESD mats for electronics; no dusty operations.
- **Schema**

wo_id, robot_id, fault_code, triage(severity), steps[], parts_used[],

calibrations_done[], test_results_url, return_to_service_ts, qa_signoff

Availability & reliability KPIs

- Fleet availability ≥ **92%**; Mean Time Between Unscheduled Removal (MTBUR) ↑ quarter-over-quarter.
- Repeat fault within 30 days < **3%**; calibration drift alarms < **1%/week**.
- Battery pack SOH > **80%** for ≥ 80% of packs in service.

Safety systems

- Battery fire blankets, Class D extinguishers, eyewash, spill kits.

- Lock-out/tag-out on high-energy bays; interlocks prevent charging during wash line operations.

12.3 Worker roles inside: planners, dispatchers, mechanics at clean benches, QA reviewers

Operating model. All human work occurs **indoors**—glass-walled control rooms, clean benches, and training bays. Emphasis on cognition, quality, and ethics; zero routine outdoor exposure.

Core roles & responsibilities

- **Planner (Ops engineering):**
    - Builds daily routes & task recipes (street hygiene, ag passes, utility jobs).
    - Sets **SLO targets** per zone; pre-allocates reserves for clinics/schools.
    - Coordinates with weather/dose telemetry to throttle tasks.
- **Dispatcher (Mission control):**
    - Live fleet map; handles **teleop triggers**; assigns teleop operators.
    - Conflicts resolution (route overlaps, geofence edits).
    - Issues public dashboard updates (coverage, advisories).
- **Teleop Operator (Licensed):**
    - Takes over on crisp triggers; follows WIs; returns to autonomy ASAP.
    - Logs interventions (why, duration, outcome); respects privacy boundaries.
- **Mechanic/Technician (Clean bench):**
    - Executes MRO work orders; maintains tool library; runs calibrations.
    - Manages **sacrificial skins** and consumable stocks; battery/fuel swaps.
- **QA Reviewer / Data Verifier:**
    - Audits **passports** (tote, shield, wash, WI logs); checks torque curves, spectra MDAs, photos.
    - Flags anomalies; triggers re-gate or re-work; maintains evidence archive.
- **Filter/Sludge Tech:**

    - Operates filter press; drums cakes; reconciles **filters-in vs hours-run**; manages rack capacity.

- **Training & Safety Lead:**
    - Runs drills (failover, dose excursion, wind gust); certifies teleop; maintains SOP posters.

Staffing patterns

- 24/7 **dispatch** with staggered overlaps; MRO day + swing; night wash-line crew.
- Surge roster for storms/hazmat with mutual-aid agreements.

Work surface & ergonomics

- Height-adjustable benches; anti-fatigue mats; low-glare lighting; acoustic treatment in control room.
- Heads-up displays for teleop; haptic joysticks; standardized hotkeys.

Training & certification

- **Onboarding (2 weeks):** H/A/R doctrine, SOPs, privacy & equity modules.
- **Quarterly recert:** teleop sims, WI refreshers, emergency tabletop.
- **Cross-training:** planners rotate through dispatch; mechanics through QA for empathy & redundancy.

Performance & ethics KPIs

- **Zero** routine outdoor human hours; intervention rate within bands; SLO compliance ≥ targets.
- Equity dashboard green ≥ **95%** of days; **appeal path** latency < **24 h**.
- QA catch-rate (issues found before public impact) ≥ **90%**.

Culture & communication

- Daily **stand-ups**: last-shift anomalies, weather/dose outlook, main tasks.
- **Blameless postmortems** on SLO misses; publish redacted summaries.
- **Open artifacts:** raw spectra/photos/logs accessible to community auditors.

Cross-cutting guardrails for §12

- **Monodirectional hygiene** through the wash line—never bypass.
- **Measured release** to the clean side (portal + photos + logs) or it doesn't cross.
- **No exception for convenience.** If something can't be deconned, it's quarantined or redesigned.
- **Evidence by default:** every wash, fix, swap, and calibration emits machine-readable logs & human-readable receipts.

Bottom line: Robust wash trains, disciplined MRO, and clear indoor roles turn a complex robot city into a **predictable, auditable machine**—keeping humans comfortable inside while the fleet does the outside work day after day.

13) Dashboards & KPIs (beyond data logging)

Purpose: Turn millions of robot events into **operational decisions** you can see at a glance, audit in detail, and govern with service guarantees.

13.1 Output metrics: hectares tended/day, km swept, valves serviced, kWh restored, totes delivered

Operator view (top row tiles)

- **Hectares tended (ag):** Σ bed_area_serviced_today (seed/weed/spray/harvest).
    - Drill-down: by crop, by tunnel ID, pass type; rework rate (% cells revisited < 72h).
    - Target: ≥ **120 ha/day** (pilot city), rework < **8%**.
- **Km swept (streets):** Σ curb_meters_cleaned / 1000.
    - Add **grate dwell compliance** (% grates paused ≥ 8 s).
    - Target: ≥ **98%** network daily; grates ≥ **95%**/day.
- **Valves serviced (water):** count(unique valve_id with action).
    - Attach torque-curve pass rate; mean time-to-isolation for incidents.
    - Target: isolation ≤ **60 min**, PM completion ≥ **98%/yr**.

- **kWh restored (power):** energy at meters returned to service × outage duration avoided.
    - Show SAIDI/SAIFI deltas from robotic response.
    - Target: trending ↓ 10–20% YoY in pilot feeders.
- **Totes delivered (goods):** count(released totes) with P90 door-to-door latency.
    - Target: P90 ≤ **4 h** citywide; clinics/schools ≤ **2 h**.

Maps & bars

- Hex-grid map with **throughput heat** (green = on pace, amber = lag, red = miss).
- "Bottleneck bar" ranks top-10 slow segments (e.g., alley blockages, high ΔP routes).

Quality hooks

- **First-pass success** (e.g., tote release, clamp install, PV swap) with **reason codes** for failures.
- **Tool utilization** & **garage capacity** to forecast tomorrow's output.

13.2 Safety metrics: dose avoided, hotspot closure time, decon pass rate

Dose avoided (the north star)

- **Definition:** Σ (human_work_hours_replaced × baseline_task_dose_rate) – Σ (incidental indoor worker dose)
    - Baseline_task_dose_rate from historical/IAEA job classes or site-specific measurements.
    - Display **MTD / QTD / YTD** with confidence bands.
- **Tile:** "Dose Avoided: **XX mSv (YTD)**" with sparkline; click for job-class breakdown.

Hotspot closure time

- **Definition:** t_close – t_detect where t_close is first map cycle showing cell below threshold & verified.
- Tracked by class: street dust, utility cut site, ad hoc spill, plume anomaly.
- Targets: street dust ≤ **6 h**; utility cut **≤ 45 min** with shields; spills **≤ 60 min** to cold.

Decon pass rate (robots/tools)

- **Definition:** % wash cycles released on first pass (portal + vision).
- Breakout: by line (standard/deep/splash), by tool family.
- Targets: ≥ **98%** first-pass; portal alarms < **0.5%** cycles.

Other safety tiles

- **Gamma-gate holds (goods):** count & % of totes/lockers held; median resolution time.
- **MDA coverage:** % map cells hitting required MDA (e.g., Cs-137) with average count time.
- **Aerosol discipline:** % wet tasks with curb socks; runoff capture rate ≥ **95%**.

Alerts (actionable, not just red dots)

- **"SLO slip—Dose Map Refresh < 95%"** → auto-queue extra UAV sorties.
- **"Portal false-positive trend ↑"** → open calibration ticket; show affected locks.
- **"Delta-P surge on sweepers (Zone 3)"** → route to garage; schedule spare heads.

13.3 Equity metrics: route latency by zip, first-priority delivery compliance

Why: Safety that is uneven isn't safety.

Latency parity

- **Metric:** P90(latency)_zip / median(latency)_city for deliveries, street sweep passes, outage restoration.
- **Goal:** ≤ **2.0×** for all zips (hard SLO).
- **Visualization:** choropleth with **parity index**; table lists zips breaching goal and remedial routes scheduled.

First-priority delivery compliance

- **Metric:** % of first-priority endpoints (schools, clinics, public kitchens) served within SLA
    - Food totes ≤ **2 h**; filters ≤ **24 h**; utility restore arrival ≤ **15 min**.
- **Display:** checklist tile (✓/% per category) with fail reasons and next ETA.

Coverage fairness

- **Street hygiene equity:** percent of **daily curb meters** per zip vs their share of total; show **gap** (±).
- **Outage burden share:** minutes of outage per capita by zip (rolling 30 days).
- **Escalation:** when a zip breaches two equity KPIs in 24 h → automatic **surge plan** (extra mules/sweepers) and a public note.

Accessibility

- **No-app access rate:** % of deliveries completed via **PIN/paper ticket**; track misses by socioeconomic index to catch digital divide problems.

Dashboard mechanics (shared)

States & colors

- **Green:** ≥ target; **Amber:** within 10% of miss; **Red:** miss. Tooltips show SLO text and auto-mitigation now in effect.

Audit-first UX

- Every tile links to **evidence**: photos, spectra, torque curves, wash receipts, lock cycle logs.
- **Download** CSV/JSON for public auditors; **append-only** logs with hash chain.

Schemas (event → metric)

event_id, ts, actor_id, zone_id, task_type, outcome, duration_s,

evidence_url, geometry_id, mda_cs137_bqkg(optional), pm25_pre/post(optional),

latency_s(optional), zip_code(optional), priority_flag(optional)

Forecast & staffing

- Burn-down chart vs tomorrow's weather/dose forecast; garage capacity bars (wash line, charge bays, MRO slots).
- "What-if" toggles (e.g., +2 sweepers, −1 UAV) update predicted KPI attainment.

Privacy & safety

- Public dashboards blur faces/windows; show **aggregates by zip**; raw media with PII gated to authorized reviewers.
- Indoor cameras/locations never exposed.

Governance hooks

- **SLO contracts** wired to tiles; breaches auto-open a ticket with owner & ETA.
- **Appeal button** for residents on delivery/hold decisions; timer on response SLA (< **24 h**).

Bottom line: These dashboards aren't pretty charts—they're **levers**. They surface output, safety, and fairness together, tie them to **automatic mitigations**, and keep every claim backed by exportable evidence so the public can verify the work.

14) Governance, Contracts, and Equity

14.1 Open job logs (who did what, when, with what shield geometry)

Principle: "Evidence before assurance." Every outdoor task emits a public, append-only **Job Log** that links to the underlying artifacts.

Minimum disclosure (public by default)

- **Who/what:** robot_id, operator_id (pseudonymous), vendor_id, tool/end-effector IDs.
- **When/where:** timestamps (start/stop), GPS/polyline, zone_id, zip_code.
- **Why/how:** WI/SOP name & version, autonomy tier, teleop minutes, exceptions.
- **Safety context:** dose rates (pre/post), **shield geometry** (panel material, thickness, layout, water-wall volume, berm length).
- **Outcomes:** pass/fail criteria, rework flags, disposal stream & chain-of-custody IDs.

Canonical schema (public)

job_id, ts_start, ts_stop, task_type, wi_version, robot_id, vendor_id,

operator_pseudo, route_geom_url, zip, dose_pre_uSvph, dose_post_uSvph,

shield:{type[], thickness_mm[], layout_ref, waterwall_L, berm_m},

tools:[{tool_id, hours_run, torque_curve_url?}], autonomy_tier, teleop_min,

evidence:{photoset_url, spectra_url?, torque_curves_url?, wash_receipts_url},

outcome:{status, reasons[], rework_needed(bool)}, custody_ids[], notes

Integrity & retention

- **Hash-chained** log blocks; daily anchor to a public ledger.
- Retain raw artifacts ≥ **7 years**; derived dashboards can be pruned.
- Redaction only for PII/private interiors; record redaction reason & hash of original.

Oversight

- Quarterly third-party audits (technical + equity).
- Community Review Panel (clinics/schools/public kitchens, labor, disability advocates) with read access to raw logs and the right to publish minority reports.

14.2 Service guarantees for clinics/schools/public kitchens; penalty clauses for misses

Service-Level Objectives (SLOs) → Contractual Service Guarantees (CSGs)
Convert SLOs into **pay-for-performance** with automatic remedies.

Priority endpoints (Tier-1)

- Clinics, schools, public kitchens, elder centers, shelters.

Example guarantees (extracts)

- **Food delivery:** *P90 latency ≤ 2 h* from depot handoff.
  Remedy: credit equal to **200%** of delivery fee for each late tote; if P90 miss persists > **2 days**, vendor pays **surge operations** (extra routes) and funds **reserve pantry draw**.
- **Filter swaps (RO/HEPA):** *≤ 24 h* from alert.
  Remedy: vendor supplies **loaner units** + filters at no cost; **$X/hr** liquidated damages thereafter.
- **Outage first-response:** *robot on-scene ≤ 15 min; temporary isolation/restore ≤ 60 min.*
  Remedy: $/minute credit to the city's resilience fund; after **3 events/quarter** miss → **corrective action plan** with public milestones.

Escalation ladder

1. **Auto-mitigation:** reserve fleet dispatch, route rebalancing, indoor HEPA cadence bump.
2. **Vendor notice & cure (72 h)** with daily public status.
3. **Independent review** (10 business days).
4. **Sanctions:** per-event credits → quarterly fee at-risk → **partial suspension** of routes → **termination for cause**.

Equity guardrails baked into contract

- **Latency parity cap:** P90 latency by zip ≤ **2.0×** city median; breach → automatic **surge plan** and fee-at-risk.
- **Coverage parity:** daily curb-meters swept per zip within **±10%** of its network share, averaged weekly.
- **Transparency:** vendor must expose **raw logs** (not only "scores") via API.

Force majeure & safety

- Weather/dose exceptions allowed only if **pre-declared** and **evidence-backed** (wind logs, portal counts). Default to **safe stand-down** + **indoor mitigations**.

14.3 Privacy & consent: outdoor video rules; indoor boundaries

Red lines (non-negotiable)

- **No indoor cameras or mics** on service robots. Ever.
- **No facial or license-plate identification**; on-device blurring for faces/windows; raw, unblurred media stored only for incident forensics with strict access logging.
- **No sale of operational data**; usage limited to safety, maintenance, audit, and research approved by the Community Review Panel.

Outdoor video/audio policy

- **Purpose limitation:** navigation, safety, evidence.
- **Minimization:** short retention for routine footage (≤ **72 h**), long retention for incident-tagged clips only.

- **Notice:** visible decals on robots; public webpage with live fleet map, purpose statements, data dictionary, and retention tables.
- **Access:** residents can request clips that include their property frontage; response **≤ 10 business days**; PII redacted.

Consent & accessibility

- Deliveries must work **without apps** (PIN, paper tickets).
- **Opt-out zones** (e.g., domestic violence shelters) can request **reduced vantage** and **no photo storage** while preserving safety logs.

Data governance mechanics

- **DPIA** (Data Protection Impact Assessment) published pre-deployment and on major changes.
- **Role-based access control (RBAC)** with quarterly access reviews; all exports are **watermarked & logged**.
- **Breach protocol:** notify within **72 h**, publish root cause and remediation; community Q&A session within **14 days**.

Research & innovation safeguards

- Sandboxed datasets (blurred/anonymized) for academic use; **no re-identification** clauses; results must be open.

Example contract language (starter clauses)

Open Logs Clause

Vendor shall provide an append-only Job Log per §14.1 via HTTPS API and weekly signed archives. Logs shall include shield geometry and pre/post dose readings. Failure to maintain verifiable continuity (hash chain) constitutes a material breach.

Priority Endpoint SLA Clause

Tier-1 endpoints (clinics, schools, public kitchens) shall meet the Service Guarantees in §14.2. Remedies apply automatically and are visible on the public dashboard within 24 hours.

Equity Parity Clause

Vendor will maintain latency parity ≤ 2.0× of city median across all ZIP codes (rolling 7-day). Breaches trigger an automatic surge plan and place 15% of the quarterly fee at risk.

Privacy Boundaries Clause

Robots shall not capture indoor imagery or audio. Outdoor video is blurred on-device for faces and windows. Routine footage retention ≤ 72 hours unless incident-tagged. Any deviation is grounds for immediate suspension.

Data Use & Access Clause

Operational data shall not be sold or used for unrelated analytics. Role-based access, audit logs, and quarterly public reports are mandatory. Community Review Panel retains authority to audit raw artifacts.

Governance in practice (how the public sees it)

- **Live "contract tiles"** on the public dashboard show each guarantee and yesterday's compliance, with links to the underlying **Job Logs**.
- **Appeal button** on delivery/hold decisions (response SLA ≤ **24 h**; independent lab path available).
- **Quarterly town halls** publish SLO misses, remedies paid, equity metrics, and audit findings—plus the vendor's corrective actions.

Bottom line: Governance is not a memo—it's **machine-readable contracts, verifiable evidence, automatic remedies, and meaningful privacy boundaries**. If it isn't logged, auditable, and fair across neighborhoods, it doesn't count.

15) Rollout Roadmap & Training

15.1 90-day pilot: one neighborhood, minimal viable fleet & airlocks

Goal (one-sentence): Prove "humans indoors, robots outside" end-to-end in a **1–2 km²** neighborhood with measurable SLOs and public transparency.

Scope & success criteria

- **Coverage:** ≥95% curb meters swept daily; ≥90% dose-map refresh / 24 h.

- **Food logistics:** ≥99.5% first-pass tote releases; P90 delivery latency ≤4 h (≤2 h for clinics/schools).
- **Utilities:** first robot on power/water ticket ≤15 min; temporary restore ≤60 min.
- **Equity:** latency parity by zip (pilot vs city median) ≤2.0×.
- **Safety:** zero routine outdoor human hours; wash-line first-pass ≥98%.

Minimal viable fleet (MVF)

- **UAVs (x4):** survey + light payload.
- **Sweep mules (x3):** HEPA vac + sticky roller.
- **Logistics mules (x2):** tote delivery + waste pickup.
- **Utility crawler (x1):** valves/hydrants + leak assess.
- **Manipulator base (x1):** light cutting/bolting/shielding.
- **Garage & wash:** 1 line (air-knife/mist/squeegee/portal).
- **Airlocks:** 2 goods lockers, 1 waste lock, 1 tool/service lock.

Week-by-week

- **Weeks 0–2 (Mobilize):**
    - Lease depot; install wash line; stand up cloud + dashboards.
    - Pre-flight safety review; privacy DPIA; publish data dictionary.
    - Community onboarding (mailers, posters, hotline, public map).
- **Weeks 3–4 (Dry runs):**
    - Route shakedown at night; failover drills (link/power/wind).
    - Goods lock calibration; tote passports; sample “holds” to lab.
    - **Exit gate:** first clean day with ≥90% curb coverage and zero portal alarms.
- **Weeks 5–8 (Live pilot - Phase A):**
    - Daily street hygiene, dose mapping, 20 totes/day deliveries, weekly hydrant PM.
    - Utilities: 1 planned valve job; 1 simulated leak clamp.
    - Publish daily dashboard (output + equity tiles).

- **Weeks 9–12 (Live pilot - Phase B):**
    - Add farm-to-A-zone harvest (1 tunnel), roof/gutter service on two buildings, one shielding job.
    - Run **storm playbook** drill (dust or rain).
    - Third-party audit of Job Logs; town-hall review.
- **Day 90 decision:** If ≥80% of SLOs are green for 14 consecutive days → proceed to sector scale-up.

Pilot risks & mitigations

- **Portal false holds:** increase count time; recalibrate; "K-rich" rule.
- **Public confusion:** staffed hotline; "What the beacons mean" cards; citizen course slots (see 15.3).
- **Fleet shortfalls:** mutual-aid stub (neighbor depot) and rental options pre-negotiated.
- **Weather spikes:** pre-declared thresholds; automatic indoor HEPA cadence bump.

Pilot budget (order-of-magnitude)

- Capex: depot fit-out + wash + lockers + MVF = **$1.8–2.5M**.
- Opex (90 days): staff, filters, consumables, insurance = **$0.8–1.1M**.

15.2 City scale-up: sector garages, mutual-aid, spare pools

Topology

- **Sectors:** 4–8 geographic sectors (50–150k residents each) with a **Sector Garage** and 3–5 neighborhood airlock clusters.
- **Backbone:** citywide telemetry (dose/PM/water) + shared dispatch; sector autonomy for day-to-day.

Fleet per sector (typical)

- **UAVs x8**, **sweep mules x8**, **logistics mules x6**, **utility crawlers x3**, **boom/manipulator x2**, **roof/facade set x1**, **vactor/jet set x1**.
- **Wash lines x2**, **airlocks:** goods x6, waste x2, tool x2.

Spare pools & readiness

- **Warm spares (10–20%)** per class parked city-central; **cold spares** for long-lead items (arms, membranes, HEPA H14 cassettes).
- **Parts ladders:** same-day, 72-h, 2-week kits; vendor SLAs with fee-at-risk.

Mutual-aid

- **MOU** with nearby cities/utilities: common log schema, radio bands, Job Log API; quarterly joint drills.
- **Strike packages:** "Dust surge set," "Utility clamp set," "Shield-and-cut set" with pallets pre-staged.

Scale-up milestones (6–18 months)

1. **Q1:** Two sectors live; cross-sector surge tested; equity tiles published citywide.
2. **Q2:** All sectors street hygiene + deliveries; utilities jobs at scale; roof/facade on priority buildings.
3. **Q3:** Full emergency services (fire/med/hazmat) robotized; research pilots (adaptive mapping).
4. **Q4:** Contract refresh with **equity parity** and **penalty clauses** tuned by data (see §14).

Citywide KPIs

- SLO attainment ≥95% days/quarter; fleet availability ≥92%; hotline satisfaction ≥90%; appeals resolved ≤24 h; **dose avoided** sparkline trending up.

Governance cadence

- Monthly sector reviews; quarterly public report & town hall; annual third-party audit of privacy, safety, and equity.

15.3 Training: 8-hour dispatcher/teleop, 90-minute citizen course on airlocks & alerts

A) Dispatcher/Teleop Operator — 8 hours (certification)

- **Module 1 (60 min): H/A/R doctrine & ethics**
    - ALARR, equity tiles, privacy boundaries, evidence-first mindset; tour of dashboards.

- **Module 2 (90 min): Fleet & tooling**
    - Robot classes, end-effectors, wash line, airlocks, Shield Passports; hands-on tool tagging/quick-change.
- **Module 3 (120 min): Autonomy → Teleop**
    - Route-follow, supervised autonomy, adaptive tasking; **crisp triggers** to take over; haptic controls; snap-back to autonomy.
    - **Sim drills:** curb clog, valve torque spike, film tear, dose excursion, wind gusts.
- **Module 4 (60 min): WI & SOP execution**
    - Walkthrough: **Harvest-under-film**, **Valve-leak**, **Shield-and-cut**; pass/fail criteria, chain-of-custody.
- **Module 5 (60 min): Safety envelopes & failovers**
    - Geofences, micro-fences, RTH/roost/tether; link/power/weather tables; incident report writing.
- **Module 6 (60 min): Privacy & public interface**
    - Outdoor video rules, no indoor capture; dealing with bystanders; clear speech scripts.
- **Assessment (30 min):** proctored teleop sim + 10-item scenario exam.
    - **Certification threshold:** 90%+ on exam + safe completion of two sim incidents in <6 min.

Continuing ed

- **Quarterly re-cert (2 h):** failover drills, new WIs, audit feedback.
- **Annual (4 h):** emergency services cross-train; joint drill with fire/water/power ops.

B) Citizen Course — 90 minutes (airlocks & alerts)

- **Why this matters (10 min):** dust → dose; what robots do; what the dashboards show.
- **Airlock etiquette (20 min):** how goods/waste locks work; what the lights mean; **no exceptions** for convenience.
- **Deliveries & holds (15 min):** tote passports, “hold” reasons, appeals path, picking up with **PIN/paper** (no app required).

- **Alerts & drills (15 min):** what beacon cones mean; dust surge & shelter steps; AED drone handoff basics.
- **Privacy & consent (10 min):** outdoor video rules; how to request/redact footage of your frontage.
- **Hands-on (15 min):** demo goods locker cycle; scan a sample dose ticket; read a Shield Passport.
- **Q&A (5 min):** hotline, website, office hours.

Accessibility

- Sessions in multiple languages; captions; large-print handouts; child-care corner; recordings posted.
- Traveling kiosk to libraries/schools; **"train-the-trainer"** kits for community leaders.

Training KPIs

- Dispatcher/teleop pass rate ≥90%; first-week intervention errors = 0.
- Citizen attendance: ≥10% of households in pilot; post-session confidence ≥80%.
- Post-training incident metrics: appeals latency <24 h; locker misuse tickets ↓ ≥50%.

Bottom line

Start small, measure everything, publish the evidence, and train both the **operators** and the **neighbors**. In 90 days you prove safety and service; in 12–18 months you scale by sectors with mutual-aid and spares; along the way you build a culture—**indoors—**that knows exactly how the robot city works and how to hold it accountable.

16) Research Agenda (brief)

16.1 Radiation-hard perception; low-cost end-effectors for dirty tasks

A) Radiation-hard perception (sensors + compute)

- **Problem:** Gamma/neutron fields induce noise, drift, and single-event upsets (SEUs) in imagers, LiDARs, and onboard compute—degrading SLAM, defect detection, and safety envelopes.

- **Work packages:**
    1. **Dose-aware sensor fusion.** Train models that ingest sensor health (dark current, LiDAR dropouts, IMU bias) and output confidence along with detections; switch to “guardian” behaviors when confidence falls.
    2. **Hardened pipelines.** Evaluate CMOS vs sCMOS vs global-shutter CCD under cumulative dose; test LiDAR APDs vs SiPMs; quantify SEU rates on common SOCs (ARM, Jetson) with ECC, watchdogs, duplicated inference.
    3. **Self-cal & drift nets.** On-board radiometrics to auto-recalibrate exposure-stressed cameras; learnable bias correction using AprilTag boards at garages.
    4. **Shielding geometry search.** Co-design sensor pods and micro-shields (tungsten/steel/water) with ray-tracing to minimize mass for given MTF/SNR.
- **Benchmarks & metrics:**
    - **Perception under dose:** mAP / mIoU vs accumulated mGy; SLAM absolute trajectory error vs dose; SEU-induced reboot MTBF.
    - **Latency/energy:** FPS and Wh per hour in guardian mode.
- **Artifacts:** Open “RadPerceptionSet”—paired scenes at stepped doses (0→10^3 mGy), raw frames + LiDAR + spectra + ground truth.

B) Low-cost end-effectors for dirty tasks

- **Problem:** Many outdoor jobs hinge on rugged, *cheap* tools that can be sacrificed or rebuilt quickly.
- **Work packages:**
    1. **Tool libraries at <$300 BOM:** vacuum wands, squeegee skids, clamp installers, valve sockets, adhesive roller cassettes—designed for 3D-printable frames + COTS seals.
    2. **Hot-swap standards:** mechanical + electrical quick-couplers with EEPROM tags; drop-test and slurry ingress tests.
    3. **Predictive wear models:** ΔP/torque signatures → remaining-life predictors; schedule swaps before failures.
- **Metrics:** $/operating hour, mean swap time, debris capture efficiency (% fines), rework rate after tool use.

- **Artifacts:** Step-files, test rigs, and reference PM curves under sand/dust/wet slurries.

16.2 Adaptive scheduling across mixed fleets under weather and dose constraints

A) Formulation

- **Objective:** Maximize SLO attainment (coverage, latency, safety, equity) while minimizing risk and energy, across UAVs/UGVs/manipulators.
- **State:** live dose/PM/wind fields; fleet health; battery SOC; airlock queues; equity debt per ZIP; tool availability; road closures.
- **Constraints:** weather caps (wind/vis), dose caps (robot & area), energy/resupply, geofences, priority endpoints (clinics/schools).

B) Algorithms to compare

1. **Stochastic MPC** (receding horizon) with chance constraints on wind/dose; replans every 5–10 min.
2. **Multi-agent RL** with *safety shields* (formal policies that block unsafe actions) and equity-aware reward shaping.
3. **Robust orienteering/vehicle routing** with time-dependent edge costs (gusts, PM spikes) and *mandatory refresh* cadence.
4. **Restless bandits** for patrols (dose map refresh, grate service) with informational value terms (MDA reduction).

C) Equity & safety as first-class citizens

- **Equity ledger:** penalty grows with latency disparity; scheduler prioritizes high-debt zips until parity ≤2×.
- **Safety guards:** hard constraints on dose/wind; automatic fallback to "guardian routes" and indoor mitigations when infeasible.

D) Evaluation protocol

- **Sim-to-field loop:** start with city digital twin (weather + plume + traffic); run A/B policy trials; then weekly field validations.
- **KPIs:** SLO hit rate, hotspot closure time, dose avoided (mSv), energy/route, % autonomous vs teleop, equity parity index, robustness under 95th-percentile gust/dust days.

- **Stress tests:** comms dropouts, sudden plume spikes, multi-incident stacking, airlock bottlenecks.

E) Tooling & releases

- **Open scheduler** reference (gRPC APIs to dispatch, wash, airlocks).
- **Scenario packs:** "Dust storm surge," "Valve burst," "Farm harvest peak," with canonical logs for reproducible comparisons.
- **Human-in-the-loop UI**: sliders for equity weight, risk tolerance; "why this route?" explanations for auditability.

Bottom line: Make perception *robust under dose*, tools *cheap and swappable*, and scheduling *adaptive and fair*. If these three progress together, a robot-run outdoor city remains safe, reliable, and equitable as conditions change.

17) Conclusion

17.1 From exposure labor to indoor prosperity

The central shift is moral and material: **hazard time becomes data time**. By committing to ALARR—*as low as reasonably required* for humans because robots can take the outside—cities trade PPE lines and dose lotteries for **measurable services**: clean curbs, steady utilities, safe food pathways, fast shielding. The H/A/R architecture (Human zones, Airlocks, Robot world) converts messy environments into **auditable interfaces** where every crossing is washed, gated, and logged. That reliability compounds: kitchens plan confidently, clinics stay stocked, schools open on time. Jobs don't disappear; they **move inside** and up-skill—dispatching, teleoperation, quality assurance, maintenance, governance. Equity is no longer a slogan but a dial on the scheduler and a clause in the contract. When the public can read dose maps, see tote passports, and watch penalties auto-trigger on misses, **trust** becomes a function of evidence, not assurances.

17.2 Keeping normal life indoors while robots actually do the outside jobs

Normal life isn't a luxury—it's the metric. A city succeeds when people **cook, learn, worship, and celebrate** without stepping into dust or hotspots. The playbooks in this work—ag under film, curb-to-catch-basin hygiene, valve clamps, shield-and-cut, roof service, emergency response, waste and deliveries—prove that outdoor work can be rendered **routine, safe, and boring** by design. Tool libraries and wash trains turn unknowns into procedures; autonomy asks for help when it should; failovers are predictable; and every task emits a passport you can audit. The roadmap is pragmatic: pilot a neighborhood, scale by sectors, drill mutual aid, and train

both operators and neighbors. Do this, and “radioactive world” becomes a **managed condition**, not a sentence. People stay warm, fed, connected, and dignified inside; outside, machines shoulder the weather, the dust, and the dose—**on time, to spec, for everyone**.

References

1. **IAEA Safety Standards—Decommissioning of Nuclear Power Plants and Research Reactors.** International Atomic Energy Agency, Safety Requirements. IAEA Publications
2. **IAEA Safety Standards Series (overview & programme).** International Atomic Energy Agency. IAEA Publications
3. **Nuclear Technology Review 2024.** International Atomic Energy Agency—sections noting mobile robots for radiological scanning in decommissioning. IAEA
4. **Digital Tools, VR and Robots for Dismantling Retired Nuclear Facilities (IAEA survey).** IAEA News. IAEA
5. **DEDICATE—IAEA Coordinated Research Project on Innovative Digital Tech for Decommissioning.** IAEA News. IAEA
6. **Remote Handling Techniques in Decommissioning: An International Review.** OECD-NEA report. Nuclear Energy Agency (NEA)
7. **Application of Remotely Operated Handling Equipment in Decommissioning of Nuclear Facilities.** IAEA technical paper. INIS
8. **Radioisotope Handling Facilities & Automation of Hot Cells.** IAEA TECDOC-1430. IAEA Publications
9. **Robots for Nuclear Power Plants.** IAEA Bulletin (historical context on inspection/maintenance robots in high-dose environments). IAEA
10. **Operation and Maintenance of Nuclear Power Plants (topic page).** IAEA (context for preventive maintenance, testing, calibration). IAEA
11. **RACE—Remote Applications in Challenging Environments.** UKAEA capability overview (remote maintenance & extreme-environment robotics). UKAEA Fusion Energy+1
12. **Boston Dynamics Spot—Radiation Mapping Case Notes.** Vendor blog on autonomous mapping with spectrometry payloads. Boston Dynamics
13. **SRNL / NNSA—"See Spot Reduce Hazards to Workers".** Savannah River National Laboratory news on integrating Mirion radiation monitoring with Spot. Savannah River National Laboratory
14. **Drone-based Gamma Spectrometry for Emergencies (NaI).** *Process Safety and Environmental Protection* (application of UAV + NaI(Tl) for source chasing). ScienceDirect

15. **UAV $LaBr_3$(Ce) Gamma Spectrometry System for Point & Extended Sources.** Research article (rotary-wing platform, quantification methods). ResearchGate
16. **Fukushima Daiichi—Status of Fuel Debris Trial Retrieval (technical brief).** TEPCO reference document (robotic arm & telescopic device timeline). TEPCO
17. **AP News—Robot Retrieves First Melted Fuel Sample from Fukushima Unit 2 (2024).** AP News
18. **The Guardian—Robot Retrieves Radioactive Fuel Sample at Fukushima (2024).** The Guardian
19. **AP News—Further Delays to Full-Scale Fuel Debris Removal at Fukushima (2025).** AP News
20. **Reuters—TEPCO Halts Debris-Removal Prep after Installation Error (2024).** Reuters
21. **IAEA—Remote Technology in Spent Fuel Management.** TECDOC on benefits of remote ops for exposure reduction. IAEA Publications
22. **IAEA—Nuclear Decommissioning: Addressing the Past and Ensuring the Future.** Proceedings noting experiences with robotics & remote ops. IAEA Publications

Note: These references emphasize standards and authoritative reports (IAEA/OECD-NEA), primary operator documents (TEPCO), and recent field deployments/research on UAV/UGV radiation mapping and remote handling.